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Durability/Corrosion of Soil Reinforced Structures

Research, Development, and Technology
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FOREWORD

Soil is a poor structural material because it is weak in tension. Reinforced soil is a generic term that is applied to structures or systems constructed by placing reinforcing elements (e.g., steel strips, plastic grids, or geotextile sheets) in soil to provide improved tensile resistance. Reinforced soil structures are very cost-effective which explains why the concept has emerged as one of the most exciting and innovative civil engineering technologies in recent times. In 1985 an FHWA Administrative Contract research study was begun to develop practical design and construction guidelines from a technical review of extensive laboratory and field tests on reinforcing elements or several reinforced soil structures. This report should interest geotechnical and bridge engineers who are concerned with durability and corrosion behavior of reinforced soil structures.

Additional copies of the report are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, Virginia 22161.

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Director, Office of Engineering and Highway
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NOTICE

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16. Abstract

This report is intended to provide criteria in evaluating potential corrosion losses when using coated or uncoated steel reinforcements, and in determining aging and construction damage losses when using geosynthetic reinforcements. To monitor in-situ corrosion rates of bare or galvanized steel reinforcements, remote electrochemical measurement equipment has been developed, evaluated and demonstrated on 7 field sites. The prototype equipment has been delivered to FHWA for further use.

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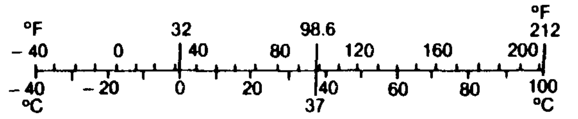
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1 INTRODUCTION

1. Purpose and Scope

Soil reinforcement, which may be defined as the inclusion of tensile resistant elements in the soil mass to improve its mechanical properties, has emerged over the last 20 years as a most exciting and innovative civil engineering technology. It is estimated that over 14,000 structures using this concept have been constructed to date worldwide and approximately 4,000,000 ft.^{2} (371,600 m^2) of earth-reinforced structures are being constructed yearly in the United States alone.

The design of reinforced soil structures requires that the combination of a select soil and reinforcement be such that the interaction between the two materials produces a composite structural material that combines their best characteristics. The judicious placement of reinforcements in the select soil mass, serve to restrain the deformation of the soil in the direction parallel to the reinforcement.

The most commonly used soil-reinforcing media to date has been galvanized steel either in strip or grid configuration (95 percent of applications to date), connected to a precast concrete facing. Aluminum alloys and stainless steel have been used for reinforcements mainly in France. Their use has been discontinued due to extremely poor performance.

The major design concern for reinforced soil structures has been the durability of reinforcements in the soil/water environment in which they are placed.

Considerable use has been made recently of polyethylene, polypropylene, polyvinyl chlorides, high tenacity polyester fibers and composite plastics such as thermoset resins as reinforcements. Though these materials do not corrode by electrochemical attack, they can suffer degradation of their structural properties during exposure to an in-soil environment, and significant damage during installation.

This manual is intended to provide criteria to guide design engineers in evaluating potential corrosion losses when using coated or uncoated steel reinforcements, and similarly in determining aging and construction damage losses when selecting geosynthetic reinforcements. In addition, remote electrochemical measurement equipment has been developed to measure in-situ corrosion rates of galvanized and bare steel and its applicability demonstrated.

The scope of this manual includes:

- Evaluation of the corrosion/deterioration mechanism which occurs in reinforced soil structures, leading to recommendations of design procedures.
- Development and demonstration of techniques and instrumentation designed to measure in-situ corrosion rates of steel reinforcements in reinforced soil structures.
- Evaluation of laboratory test methods for the electrochemical analysis of select backfill materials used in reinforced soil structures.
- Development of criteria to determine survivability of fusion bonded epoxy coatings.
- Development of criteria as related to survivability of geosynthethics used in reinforcement applications, leading to the development of recommended design strengths.

As with any developing technique or materials, not all of the principles or processes are completely understood, nor can all of the variables be directly taken in account. For this reason, the data and recommendations contained in this manual should be considered as a guideline for design and implementation of field measurement programs.

2. Background

(a) Components of Reinforced Soil Structures

Retaining structures using this technique are now being generically referred as Mechanically Stabilized Earth (MSE) due to the expiration of the basic concept patents and a proliferation of suppliers and manufacturers providing the required manufactured components. All systems consist of four interrelated elements:

- The reinforcing elements in either strip, grid or sheet form, fabricated from metals or geosynthetics.
- The connection between facing units and reinforcing elements.
- The facing units, usually discreet reinforced concrete panels of square or rectangular geometry. Wood, plastic or metal facings have been used as well.
- The select granular fill.

Reinforced soil slopes, comprise a second type of structure utilizing this concept. They are used to construct steep slopes not normally safe if constructed without reinforcement. Facing elements are normally formed by wrapping the sheet or grid reinforcement around the exposed soil at the face and then covering it with gunite, asphalt emulsion or with soil and vegetation.

(b) Metallic Reinforcements

Accelerated or unanticipated corrosion of the reinforcements could cause sudden and catastrophic failure of reinforced soil structures generally along a nearly vertical plane of maximum tensile stresses in the reinforcements. This plane is located at a distance varying from 0 to 0.3H from the facing where H is the height of the structure. Failures of this type have occurred in the south of France on waterfront structures and more recently on major structures located in Dunkirk and Paris, France on major circumferential highways. Progressive failures are reported to be occurring at a major ore unloading facility also in France where coal oil is in contact with a steel facing.(24)

A number of these structures have been constructed with either stainless steel similar to AISI 430 or aluminum alloys usually AG-4 MC, which is similar to the 5086 aluminums produced in the United States.

Significant failure rates using these materials has led to their discontinued use, in light of their performance and considerably higher cost. Failures have been reported with structures using galvanized steel in Spain and South Africa where a number of structures including a major cathodically protected structure. Two structures in the United States, one in Brunswick, Georgia (aluminum) and the other in Lockport, New York, (galvanized steel) have been replaced due to excessive corrosion of the reinforcements within the first 10 years of service.(24)

Since there has been only a few foundation failures during construction, accelerated corrosion during in service condition is considered the most likely long-term problem and the one which deserves the greatest attention. Present design methods rely on the addition of a sacrificial thickness to the tensile reinforcing members to compensate for corrosion losses during a projected design life. For this approach to be successful, the corrosion rate for every regime in which reinforced soil structures are constructed must be known with some degree of accuracy. Changes in these regimes must be monitored in order to determine their effects on design corrosion rates.

The development and demonstration of remote measuring techniques for steel corrosion rates is therefore an important adjunct to careful design assessment. The durability of buried steel reinforcements must be assessed on a project basis by determining the potential aggressiveness of the ambient regime.

The corrosion mechanism of ferrous and other metals in soils is essentially electrochemical. For corrosion to occur, there must be a potential difference between two points that are electrically connected in the presence of an electrolyte. Under these conditions, a current will flow from the anodic area through the electrolyte or soil to the cathodic area and then through the metal to complete the circuit. The anodic area becomes corroded by the loss of metal ions to the electrolyte.

In general, the most corrosive soils contain large concentrations of soluble salts, especially in the form of sulfates, chlorides and bicarbonates and may be characterized as very acidic (low pH) or highly alkaline (high pH).

Clayey and silty soils characterized by fine texture, high water holding capacity and consequently by poor aeration and poor drainage are also prone to be potentially more corrosive than soils of coarse nature such as sand and gravel where there is free circulation of air. Buried metals corrode significantly by the process of differential aeration and sometimes by bacterial action. Corrosion by differential aeration may result from substantial local differences in type and compaction of the soil or variations in the oxygen or moisture content resulting thereof. Such a phenomenon is generally associated with fine grained soils. Bacterial corrosion is associated with the presence of anaerobic sulfate-reducing bacteria which reduce any present soluble sulfates in the soil to sulfides. It has not been reported as a problem with galvanized steels.

(c) Geosynthetic Reinforcements

A basic requirement for reinforcement used in permanent reinforced soil structures is the ability to reliably resist sustained loads without unacceptably large deformation or tensile failure. Geosynthetic soil reinforcements do not participate in electrochemical reactions and have the advantage that they do not corrode,therefore advancing the possibility of using more marginal or aggressive fills during construction. However, the long-term effect of a buried environment can bring about changes in the residual strength and modulus of polymeric materials which are not predictable from measurements carried out under short-term controlled laboratory conditions. Equally, the exposure of geosynthetics to chemicals or solvents for environmental testing purposes can show no apparent effects as long as samples remain in an unstressed condition. However, at service stress levels and exposed to the same materials, the samples may suffer premature failure.

An additional consideration in the use of geosynthetics as soil reinforcement is that they creep under sustained tensile load. Failure occurs not at a constant dead load but at decreasing load as time to failure increases. Any tendency to creep becomes more pronounced as temperature increases and, consequently, ductile creep failure at a given stress level occurs more rapidly at higher temperatures.

Geotextiles composed of polypropylene or polyester fabrics have been used as tensile reinforcements in soil reinforced structures. Their durability for in ground use has been reported in the literature and summarized in NCHRP-290. In general, the data has shown the materials to have a loss of strength, greater elongation and significant variation in crystallinity, with time. A significant portion of the strength loss is associated with construction damage during installation.

Composite materials constructed of an inner core of polyester fibers sheated with polyethylene have been used in the Middle East and Europe in soil reinforced structures. Preliminary data suggests that some strength loss for these materials may have occurred due to deterioration by hydrolysis or other in-ground processes.

Removal tests of fabrics from underground service have reported losses of strength up to 70 percent of initial strength for a wide variety of fabrics both polyester and polypropylene. Assessment of these strength losses is crucial in the development of rational design allowables and use specification for these materials as tensile reinforcements in soil-reinforced structures. Estimates as to the longevity of thermoset resins produced as geogrids, have been made largely through accelerated laboratory testing aimed at defining their long-term creep behavior, propensity to environmental stress-cracking and degradation to strong acids or industrial solvents.

The effects on the reinforcement of chemical and biological exposure are dependent on material composition, including resin type, grade and additives, manufacturing process, and final product physical structure. For this reason, product specific studies must be carried out to assess the effects on the reinforcement's durability in differing environments.

These durability studies should include the effect on short-term and long-term mechanical properties as well as changes to the reinforcement microstructure, dimensional changes, changes in mass, oxidation, environmental cracking, hydrolysis, temperature, plasticization, and changes in surface micrology together with any variation in the infrared spectrum. The synergetic effect of different environments, particularly temperature, should be fully investigated and, whenever possible, the reinforcement should be subjected to a working stress during the environmental test.

The effects of construction damage on the reinforcements can only be determined from results of full-scale construction damage tests using representative fill materials and construction procedures.

Within the above generalized framework and product specific testing, rational design allowables can be generated for design use.

(d) Fusion Bonded Epoxy Coatings

As an alternative to the use or development of plastic material possessing the required strength and aging properties for use in reinforced soil structures, fusion-bonded epoxy coatings on steel reinforcements have been used on a number of projects and provide an alternative solution.

These coatings need to be hard and durable to withstand abrasion under normal construction conditions and have strong bonding properties to the base metal to ensure long-term integrity. Significant use of fusion-bonded epoxy protection for underground structures has been made by the pipeline industry. However, in most cases pipelines are also protected by cathodic protection in addition to coatings.

To be effective, fusion-bonded coatings must be impermeable to gases and moisture and free of gaps, even microscopically thin, at the interface between the metal and the coating. The rate and propensity of coating undercutting at flaws and its ability to withstand construction induced abrasions must be determined in order to arrive at design recommendations which would ensure longevity.

Chapter 2 CORROSION OF METALLIC REINFORCEMENT

1. General

Corrosion is the deterioration or dissolution of metal or its properties by chemical or electrochemical reaction with its environment. When a large surface is effected it can be viewed as general corrosion and approximated by an average fictitious uniform rate of corrosion per year. If confined to small points so that definite indentations form in the metal surface, it is referred to as pitting corrosion and generally reported as maximum pit depth per year.

Corrosion is fundamentally a return of metals to their native state as oxides and salts.(1) Only the more noble metals and copper exist in nature in their metallic state. Other metals are refined by applying energy in the form of heat. Unless protected from the environment, these metals revert by the corrosion process, which is irreversible, from their temporary state to a more natural state.

Although most chemical elements and their compounds are present in soil, only a limited number exert an important influence on corrosion.(2) In areas of high rainfall, the passage of time has resulted in the leaching of soluble salts and other compounds, rendering these soils generally acidic. In arid locations soluble salts are brought to the upper soil layers through capillary and evaporative processes causing the soils to be generally alkaline.(1)

The corrosion process releases the energy the metal gained during its refining in the form of electrical energy. Current flows because of a voltage difference between two metal surfaces or between two points on the same surface in the presence of an electrolyte. Two pieces of metal or two portions of the same metal in an electrolyte seldom have the same potential. The amount of potential difference depends on the nature of the metal, the condition of the surface, the nature of the electrolyte and the presence of different materials at the interface of the metal and electrolyte. The authoritative reference work to date on underground corrosion is NBS 579.(2)

2. Corrosion Indices and their Determination

The design of the buried steel elements of soil reinforced structures is predicated on the measurement of key index parameters of the backfill, which govern corrosivity, the desired life of the structure, and the assessment of such basic environmental factors as location and probability of changes in the soil/water environment from subsequent seepage of potentially aggressive elements.

Several parameters determine soil corrosivity, including soil resistivity, degree of saturation, pH, dissolved salts, redox potential and total acidity. These parameters are interrelated but may be measured independently. The direct link between any one soil parameter and a quantitative corrosion relationship has not been fully substantiated, but a general consensus has emerged from publications on studies of buried metals that resistivity is the most accurate indicator of corrosion potential.(2)(4) The influence and measurements techniques for these parameters can be summarized as follows:

(a) Soil Resistivity

Soil resistivity is defined as the inverse of conductivity. Resistivity is the convention of expressing the resistance of materials in units of ohm/cm. For more practical chemical and biological usage, the scientific community uses the algebraic inverse of ohm resistance for conductivity expressed in m'hos. The current preferred international standard SI system uses the term electrolytic conductivity expressed in units of siemen per meter (s/m) in which dS/m is the identical value to mhos/cm.

The electrolytic behavior of soils is an indirect measurement of the soluble salt content. The amount of dissolved inorganic solutes (anions and cations) in water or in the soil solution is directly proportional to the solution electrolytic conductivity. The major dissolved anions in soil systems are chloride, sulfate, phosphate and bicarbonate, with chloride and sulfate the most important anionic constituents in corrosion phenomena. The electrolytic conductivity (EC) of the soil solution is the sum of all the individual equivalent ionic conductivities times their concentration.

A number of methods are in current use to measure either electrolytic conductivity or soil resistivity directly, notably ASTM G57-78, California Test 643 or Soil Survey Lab. Procedure 8E. ASTM Method G57-78 for soil resistivity measurements in the field and laboratory, employs the use of four electrodes instead of the two required in California Test 643. The four electrode technique is an improvement over the California Test by minimizing errors due to polarization effects. Another difference in these two methods is that the ASTM laboratory measurement is conducted only at a saturated paste moisture level as in the Soil Survey Lab procedures. Conducting the analysis at the saturated paste moisture level will result in the minimum resistivity value for the in-situ soil with the possible exception of certain clay soils not used within the reinforced soil mass.

The Soil Survey Lab procedure for soil resistivity (8E) utilizes a portable Wheatstone bridge with a specially designed standard soil cup. Although this old procedure is not currently used to any great extent, it is still maintained for field mapping of saline and alkali soils.

The California Test is similar to the Soil Survey 8E method but is a much more time-consuming procedure requiring the determination of resistivity at various levels of soil moisture in a specially designed resistivity box. Inherent problems of this procedure such as repacking density, uneven moisture distribution, equilibrium time, tortuous cell path length and electrode contact variation by packing density and textural differences should lead to a low degree of intra and inter laboratory precision, accuracy and reproducibility.

Part I of California Test 643, "Method of Field Resistivity Survey and Sampling For Laboratory Tests" or ASTM Method G57-78 provides a means for readily determining the soil variability on-site and assist in selecting an appropriate sampling scheme. However, the preferred method for laboratory analysis (laboratory method of determining minimum resistance) should be an aqueous extract on a 1:2 or 1:3 soil-water ratio as described by procedure 10-2.3.2 in Methods of Soil Analysis Part 2.(45) After extraction, the electrical conductivity of the solution is determined by procedure 10-3.3 and the results can be further expressed as ppm soluble salts by using the conversion factor of 640 times mhos/cm = mg/l.

This is essentially the same procedure as for the standard methods outlined except that the soil to water ratio is greater than the saturated paste, and the conductivity reading can be converted in addition to soluble salts.

There are several important advantages by following this technique. The relatively simple and rapid procedure is virtually free of errors and extremely reproducible. No special apparatus is required beyond the standardly equipped environmental or soils laboratory. An asset of this method is that it allows the analyst to extract the soil at any soil to water ratio and express an absolute result of soluble salts on a dry-weight basis. This differs from the laboratory EC measurements on moist and saturated paste methods as denoted by the California Test 643, Soil Conservation Service Soil Survey Laboratory procedure 8A3a, and ASTM G57-78. For screening purposes, the laboratory procedure on saturated paste denoted by ASTM G-57-78 should be sufficient.

Soil resistivity has a strong influence on the rate of corrosion, particularly where macro-corrosion cells are developed on larger steel members, as it governs the effectiveness of the ionic current pathway.

Corrosion increases as resistivity decreases. However, if resistivity is high, localized rather than general corrosion may occur. Increased soil porosity and salinity decreases soil resistivity. The importance of and interaction between compaction, water content and resistivity, and their influence on corrosion processes has perhaps been under emphasized in many of the available studies.

Resistivity should be determined under the most adverse condition (saturated state) in order to obtain a comparable resistivity independent of seasonal and other variations in soil-moisture content.

(b) Moisture Content

Resistivity decreases as the water content increases and generally reaches a minimum value at 100 percent saturation and granular soils. Soil resistivity drops sharply as the water content rises from 0 to 20 percent, above which it is much less dependent on water content.

Soil structure, permeability and porosity determine the moisture content of a soil. Where the moisture content of a soil is greater than 25 to 40 percent, the rate of general corrosion is enhanced, but below this level pitting attack is more likely.

The corrosion of mild steel is enhanced when soil moisture content exceeds 50 percent of saturation. This may be compared to the critical relative humidity (rh) which occurs above ground in atmospheric corrosion.

Several researchers maintain that the critical moisture content is that value where the entire metal surface becomes electrochemically active.(1) Others have shown that corrosion increased appreciably when the moisture content exceeded 50 percent of the water holding capacity and decreases as the capacity (saturation) approaches 100 percent.(4) Stagnant groundwater in soil may provide conditions favorable for microbial attack.

(c) Soluble Salts

The amount of dissolved inorganic solutes (anions and cations) in water or soil solutions is directly proportional to the solution electrolytic conductivity. Therefore, the electrolytic conductivity (inverse of resistivity) of a soil solution is the sum of all the individual equivalent ionic conductivities times their concentration. The Soil Science Society of America and the Soil Conservation Service have adopted the relationship of the standard factor 640 times EC equals mg/l salts as a means of connecting electrolytic conductivity (EC) to total soluble salts.

Other relationships have not been found as reliable, especially at concentration of less than 100 ppm (parts per million).(1)

Most salts are deleterious, with the exception of carbonate, which forms an adherent scale on most metals and reduces corrosion. Chlorides and sulphates have been identified in the literature as being the chief agents in the promotion of corrosion.(2)

Sulphate ions in addition promote the growth of sulphate-reducing bacteria (SRB) when other conditions are suitable. Also, iron ions increase soil corrosivity where SRB attack is possible.

Therefore, the accurate determination of chloride, sulfate and sulfide portions of the total salt content are important elements in determining corrosivity.

(1) Chlorides

Chloride minerals are very soluble and thus completely removed by an aqueous extract. Chloride determination methods can be categorized as electrometric or colormetric. The electrometric methods available include potentiometric titration (i.e. Mohr argentometric), coulometric by amperometric automatic titrator, direct reading potential (i.e. selective ion electrode), or solution conductance with prior separation by ion exchange. The mercury thiocyanate colormetric method has been devised for application for autoanalyzers.

The Mohr argentometric (407A) method has been the recommended standard by the American Public Health Association (APHA, 1980). California Test 422, ASTM D-512 as well as the Soil Survey Lab procedure 6K1a employ in general these procedures. Method 65-3.5 outlined in Black, has been designed specifically for soil extracts but is, however, a preferred procedure.(3)

The procedure is nearly identical to the APHA method except for using a sodium bicarbonate buffer for adjusting the sample pH instead of sulfuric acid or sodium hydroxide. The bicarbonate is an improvement because the sample pH can be adjusted more easily without overshooting the endpoint. The California Test has some potential problems as written that may lead to inconsistent results. First, the soil extraction should be mechanically shaken to ensure complete dissolution of sand grain sized minerals. Second, the proportion and preparation of the main reagents have been altered from achieving optimum sensitivity. Shortcuts such as not running a blank determination and most importantly not requiring standardization of the silver nitrate titrant can only lead to poor analytical quality control and results.

Alternative procedures could be adopted that are applicable to automated routine laboratory instrumentation. The colormetric ferricyanide method is specifically tailored for applications in automated Technicon systems. Either method APHA 407D, USEPA staff, 1974 method 00940 for chloride or the Technicon method 696-82W describe the instrumental setup and procedure. The ferricyanide procedure also is suitable for manual determination in smaller laboratories and may be interchanged for the Mohr titration. ASTM D-4327-88 is a recently adopted standard to measure anions including chloride by ion chromatography. It is the most accurate and reproducible of all methods.

(2) Sulfates

The extraction and quantification of soil sulfur imposes a more complex problem than chloride. Sulfate represents only one of the fractions in which sulfur can exist in the soil. In addition to different sulfur forms, the inorganic sulfate may occur as water soluble (i.e. sodium sulfate), sparing soluble (i.e. gypsum) or insoluble (i.e. jarosite) minerals. The solubility of sulfate is also restricted in some soils by absorption to clays and oxides or by coprecipitation with carbonates. On the other hand, if the water extractant ratio is greater than field moisture contents, slightly higher amounts of sulfate than actually occur in the soil solution may be measured due to hydrolysis and mineral dissolution. The water-soluble sulfate will not represent the total sulfate in all soils but is an appropriate choice for quantifying the soil solution activity with regard to corrosion potential.

An array of methods with modifications for sulfur analyses have been suggested using gravimetry, turbidimetry, titrimetry, colorimetry, ion chromatography, X-ray flourescence and atomic absorption techniques. Although plagued with problems of colloidal organic matter, interferring ions as silica and calcium, barium chloride reagent crystals size, temperature, time of crystal formation and deposition of barium sulfate on the sample curvet, the turbidimetric method for sulfate still provides quantitative results, if utmost care in good analytical technique is practiced. California Test 417, method 10-3.7 in reference 45, ASTM D516 method B and APHA method 426C present the identical well established version of the turbidimetric method and should be maintained as the preferred procedure.

Automated procedures using chloranilate method 00945 (USEPA, 1974) or methylthymol blue method 426 APHA reduce human and environmental errors and also overcome matrix interferences in the analysis. Either one of these methods is acceptable as an alternative method.

Recent technical innovations in automated ion chromatography instrumentation provide an excellent further alternative. The basic operation consists of ion separation by an exchange resin followed by quantification with a conductivity detector. Most of the errors associated with classical sulfate methods are alleviated by this procedure and therefore, chromatography methods should be considered an acceptable and superior method to the classical turbidimetric method. Another attribute of this method is that chloride and sulfate are determined simultaneously with a high degree of confidence. The Soil Survey Laboratory adopted this technique for their anion analysis of soil extracts and is described as procedure 6K1c and 6L1c. ASTM D4327-88 is a recently adopted standard to measure anions including sulfate by ion chromatogaphy.

(3) Sulfides

Sulfide containing soils can cause severe deterioration of both steel and concrete. Freshly exposed sulfidic materials will have no indication of acid sulfate conditions when analyzed in the laboratory. Typical pH values will be from 6 to 8 with a low soluble salt content. Once the material is exposed to aeration by disturbance or scalping of the land surface, the sulfides oxidize chemically or via biological kinetic acceleration by Thiobaccilus ferrooxidans. Characteristics of active acid sulfate weathering include pH values lower than 3 due to free sulfuric acid generation and appearance of salt efflorences. The occurrence of sulfidic materials is generally limited to geologic formations derived from marine sediments or strata associated with coal and lignitic geologic materials.

Samples having Munsell color chromas of 1 or less (very dark gray or black) in regions noted to have sulfidic soil materials should be considered suspicious and screened for the presence of sulfides.

Because the pyritic sulfur of these materials is quite variable and no simple quantitative method is available, only screening for sulfides is recommended. If quantitative pyritic sulfur is desired, ASTM method D-2492 or the doctoral thesis "Quantitative Determination of Total and Forms of Sulfur in Soil and Geologic Materials Employing X-ray Spectroscopy", should be referred to.(46)

A qualitative test would be by oxidation of the sulfide with hydrogen peroxide with subsequent determination of the converted sulfate. Even though complete conversion is not likely by this treatment, sufficient increase in sulfate would be sufficient evidence for sulfides. A suitable procedure would involve heating a sample at 70 C with a water ratio between 1:1 to 1:2 with addition of hydrogen peroxide in increments to maintain approximately 10 percent. After oxidation is complete by subsidence of the peroxide activity, the sample should be boiled to decompose the remaining peroxide. The sample then would be filtered and the filtrant brought to a known volume for sulfate analysis. If the soil material is calcareous, the soil sample should be treated with just enough glacial acetic acid to make the sample slightly acidic by a litmus paper test prior to the addition of the hydrogen peroxide.

(d) pH

The measurement of pH represents the hydrogen ion concentration in solution. In the case of soil colloidal systems, only a small proportion (less than 1 percent of the hydrogen) is dissociated off the soil exchange complex.

Values of soil pH represent the hydrogen activity in the soil solution and are referred to as the intensity factor. Even though two soils may have identical pH values, their total exchangeable acidities (capacity factor) and thus the lime requirements to neutralize their acidities may be quite different.

The most universal procedure for measuring the soil pH is by the pH glass electrode-calomel reference electrode pH meter on a 1:1 weight ratio of soil to water. The Soil Survey Laboratory procedure 8C1a is the most followed method. Although the effects of slight modifications in the amount of soil plus water and equilibrium time as outlined in California tests 643 can be assumed to be minimal, the Soil Survey Lab procedure is preferred because of possible insufficient time allotted for equilibrium in the California test. When comparing soils with different levels of soluble salts, an optional soil pH measurement in 0.01 M $CaCl_2$ (8C1e) is advised to minimize the difference in hydrogen dissociated off the exchange complex by the differences in the salt content. ASTM G51-77 "Standard Method for pH of Soil for Use in Corrosion Testing" describes the field measurement of soil pH and should be considered as outdated.

Laboratory methods will always produce deviations away from neutrality as compared to the field moist determination. Therefore, laboratory methods provide a more conservative value for corrosion potential predictions.

For soil investigations requiring more detailed and concise interpretations of their chemical properties in relation to pH, the lime requirement as determined by the SMP buffer procedure 12.3.4-4 utilized by commercial agricultural testing laboratories is recommended.(45) The numerical values of these procedures reflect both the intensity and capacity factors of soil acidity.

In consideration of the above comparison of soil pH methodology, the laboratory method 8C1a is the preferred procedure for routine soil analyses for corrosion testing. The Soil Survey Laboratory method is preferred over the California Test because of the lack of a required equilibrium time. The California Test does not allow sufficient time for complete dissolution of salts, nor can the method be readily employed for running batch samples.

In general, as the pH value decreases from neutral, the corrosion rates of metallic reinforcement elements increase, although in the case of most high alloy steels, only very low values will have a significant effect. The measured pH is not as important a parameter as soil resistivity. In addition, pH values as a measure of corrosion, may be misleading as total acidity or alkalinity may be more important.

(e) Redox Potential

The redox potential is used to give a quantitative assessment of the type of corrosion mechanism to be anticipated in the electrolyte and to distinguish between aerobic soils and anaerobic soils that could support sulfate-reducing bacterial activity. In soil, a low value would indicate susceptibility to microbial attack, while a high value would tend to indicate the presence of oxygen supportive of long line corrosion. In general, a high value of redox potential would be indicative of cathodic sites and a low value, anodic. The less positive the redox potential, the more likely it is that microbial attack will occur especially in heavy clay soils.

A recent study of microbiologically influenced corrosion indicated that localized corrosion is more probable than general attack.(4) The development of macro-corrosion cells (long-line corrosion) in which a metallic element runs through two different types of soil, is governed by differential oxygen access to the metal. The likelihood of this type of attack can be estimated from redox measurements. One example is the corrosion of reinforcing elements near the edge of an embankment. The low oxygen zone within a soil cross-section produces a low redox potential and material within it becomes anodic and corrodes. The corrosion rate is proportional to the ratio of (metal area in high redox potential)/(metal area in low redox potential). The full expression is:(4)

$$\text{Rate} = \frac{\text{Redox difference x Metal area ratio}}{\text{Soil Resistivity}}$$

At present, there are no standard methods of measuring redox potential, NBS 579 outlines procedures commonly used by corrosion engineers.(2)

(f) Soil Compaction

Compaction of soil is defined as the elimination of air voids between particles of soil, and is measured by the mechanical compression of a quantity of material into a given volume.

When soil compaction occurs evenly, soil resistivity is consistent and in general its corrosivity is decreased. Soil permeability is reduced with compaction and provided drainage is adequate and the soil is non-aggressive (neutral or alkaline), corrosion should be decreased. However, the effect of compaction is related to soil cohesiveness. In clay soils, the corrosion rate soon after burial increases with compaction due to agglomerates on the metal causing localized attack. Well-drained granular soils having moisture contents of less than 5 percent are non-aggressive, but drainage decreases with increasing compaction leading to marginal increases of corrosion.

(g) Oxygen Transfer

Oxygen is usually transported into a bulk soil by dissolution in water, the rate dependent on the same factors which affect the gaseous state. The amount of oxygen, free or dissolved, is affected by the depth from the surface; the rate being greatly reduced as the distance from the surface is increased. The penetration of oxygen within a soil cross-section will vary according to the physical properties of a soil. Differential oxygen transfer may create areas of low oxygen concentration which become anodic and corrode preferentially. The redox potential may give an indication of the extent of oxygen transfer; a high positive redox potential indicating a higher gas transfer.

Reference 4 extensively discusses the possibility of corrosion damage occurring under conditions of alternate wetting and drying suggesting that seasonal and geographical variations in rainfall have a considerable significance with respect to the corrosion rate of buried metals. It further suggests that the time of year at which construction takes place may also affect later corrosion behavior.

(h) Organic Material

Some soils contain a high proportion of organic material where general microbial growth will reduce this to organic acids which when in contact with metals, produce pitting corrosion. The inclusion of organics in the backfill can initiate the formation of anaerobic pockets of soil which could be contaminated with sulphate-reducing bacteria (SRB), thereby initiating microbial attack in the form of severe pitting. AASHTO T-267-86 is normally used to determine organic content.

(i) Soluble Iron Content

The literature indicates that soils containing more than 125 mg Fe/gram soil are aggressive, while soils containing less than 50 mg Fe/gram soil are not.(5) Biogenic iron sulphides can be produced in high soluble iron soils. These materials are very aggressive.

3. Corrosion Rates

(a) Available Data Analysis

The most comprehensive data available in the field of underground corrosion are the results of extensive field testing on metal pipes and sheet steel buried by the U.S. National Bureau of Standards (NBS) in programs originating as early as 1910.

Additional data includes the results of the many studies conducted in the U.S. on the performance of metal highway culverts and buried piling. This data, generally qualitative rather than quantitative, is substantially in good agreement with the extensive burial tests conducted by NBS.(2)

A general conclusion of the above studies is that the rate of corrosion is greatest in the first few years of burial and then levels off to a steady but significantly lower rate.

Romanoff based on these studies, suggested the following exponential equation to predict the amount of general corrosion at some time (t) after burial:(2)

$$x = Kt^n \qquad (1)$$

where x is the loss of thickness or pit depth in the metal at time (t) and K and n are constants that are soil and site dependent (n is less than unity).

NBS determined for low alloy and carbon steels in a number of soil burial conditions a "n" constant varying from 0.5 to 0.6 and "K" constants between 150 and 180 um the end of the first year. For galvanized steels "n" constants were not evaluated, but "K" constants varying from 5 to 70 um can be inferred.

It should be noted that the NBS data was developed from a wide range of burial conditions not necessarily reflective of select backfill required for soil reinforced structures.

Standard practice in the United Kingdom with respect to providing sacrificial thickness for buried galvanized steel structures follows the above concepts and considers "n" coefficients of 0.67 and 0.80, "K" coefficients of 22.5 and 40 for soils considered non-aggressive and aggressive, respectively.(6) Aggressive soils are considered if their resistivity is less than 2000 ohm/cm. and the redox potential less than 400 mV. This practice is generally consistent with NBS data.

Various Highway Departments have conducted corrosion studies with reference to metal culvert durability, summarized in NCHRP-50.(1) This summary indicated that a number of analytical methods have been proposed by California, New York and Utah which appear to be locally satisfactory. However, no method has found wide spread acceptance. A widely used monograph developed by Stratfull in connection with California culvert studies suggests that corrosion losses for moderate to mildly corrosive soils may be on the order of 10 to 35 um/year depending on pH (figure 1). This significant dependence on pH is not widely accepted and contrary to some data developed by other highway departments.

Results from carefully controlled laboratory tests on buried box samples and electrochemical cells performed for 10 years in France strongly suggests that for the range of fills utilized in soil reinforcing application, the constant "n" may be taken as 0.60 for galvanized steel while the zinc coating is still present and from 0.65 to 1 for carbon steel once significant corrosion occurs.(7) The constant K calculated at the end of the first year, for galvanized steel was found to vary between 3 and 50; the higher values consistent with soils characterized by lower resistivities and highest concentrations of chlorides and sulfates.(8) The loss data as a function of time for these studies is shown on figure 2 and 3. This data with reference to the constant "K" has been analyzed in an attempt to determine any potential relationship with resistivity and degree of saturation. The scatter is great, but for resistivities greater than 5000 ohm/cm., the range for "K" reduces to 8 to 45 with an average value on the order of 25.

The data further suggests that once the galvanized zinc coating is depleted, the base carbon steel corrodes at the carbon steel rate. This phenomenon is clearly shown on figure 4 and 5 on which the burial data for carbon steel and lightly galvanized steel (30 um) is shown. However, it should be borne in mind that the data is too sparse to form absolute conclusions.(7,21,22)

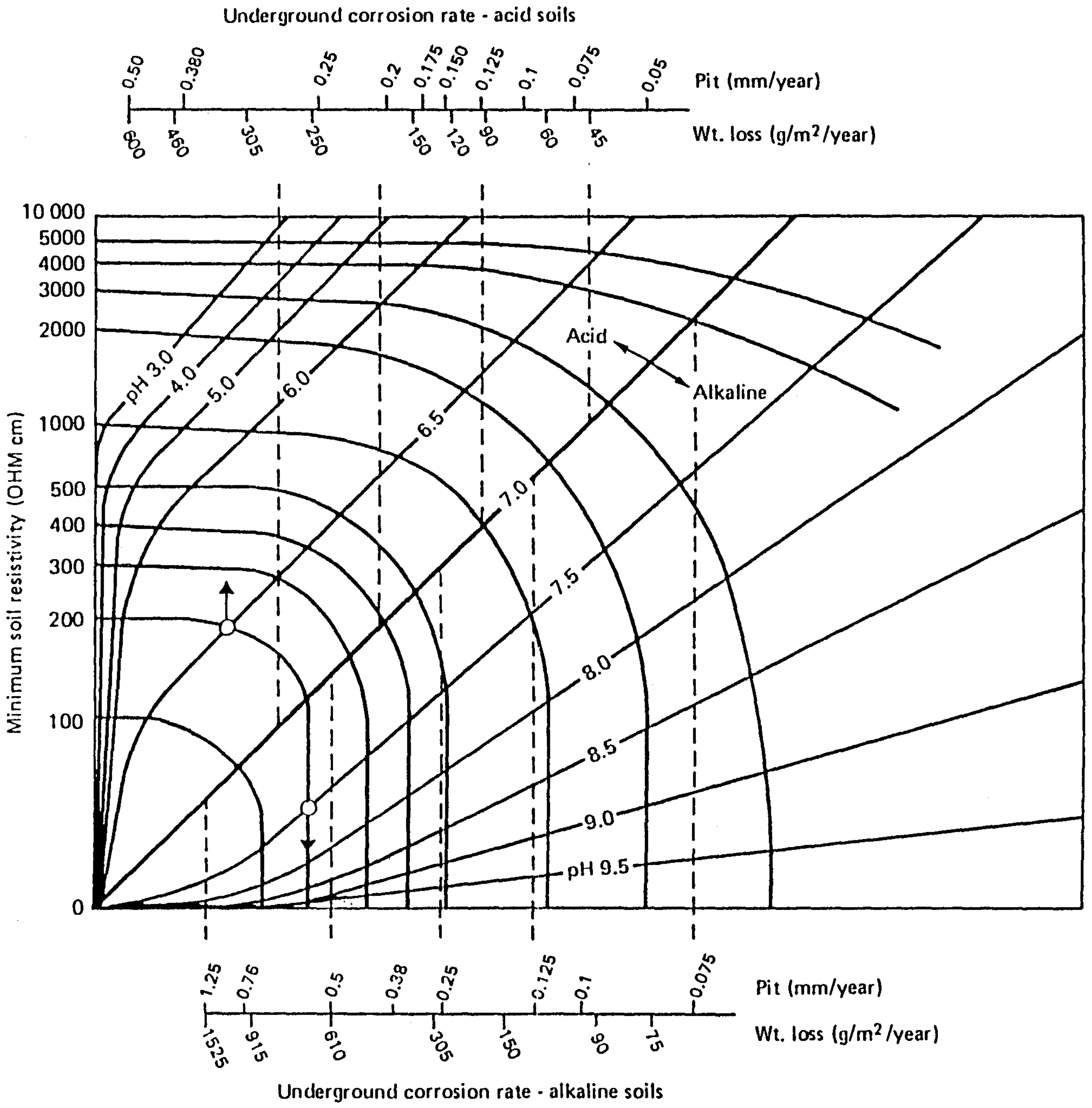
By contrast, Darbin has extended the loss rate generally obtained on galvanized samples with "n" coefficients of 0.6 to 0.65 into the carbon steel consumption phase. Such extrapolation appears unconservative in light of higher carbon steel corrosion rates (n) developed both on carbon steel samples and lightly galvanized samples. The 60 um galvanized samples, however, suggest an attenuation of the rate to "n" values on the order of 0.8. As a minimum, a continuing loss rate of this order of magnitude is believed warranted at this time.

An analysis of NBS data by Stuttgart University focused mainly on data obtained from those sites that are characterized as well draining and containing soils that are predominately granular.(9) Based on this study, the corrosion loss rates for both zinc and steel were generalized as shown in figure 6, indicating a rather rapid loss in the first 2 to 3 years for both galvanized or bare steel specimens and then continuing at a reduced lower rate.

Although corrosion rates for both galvanized steel and carbon steel with time are clearly exponential, it was believed that they could be approximated by linear extrapolation for design and comparative purposes in the limited time frame, in which reinforced soil structures are analyzed.

An analysis approach was formulated by estimating the longevity of the zinc coating based on corrosion rates observed from the data, and then by assuming continuing losses based on corrosion rates observed for the base steel. The data is based on sites characterized by the following minimum values of key backfill indicators:

pH range	4.5 - 9.5
Resistivity	> 1000 ohm/cm
Chlorides	< 50 PPM
Sulfates	< 200 PPM



e.g. with pH = 6.5 and resistivity = 200 ohm cm, the weight loss is approximately 300g/m^2/year and the pitting rate 0.33mm per year.
If pH = 7.5 and resistivity = 200 ohm cm, the weight loss is approximately 700 g/m^2/year and the pitting rate 0.55mm per year

Figure 1. Nomogram for estimating the corrosion rate of steel pipe(4)

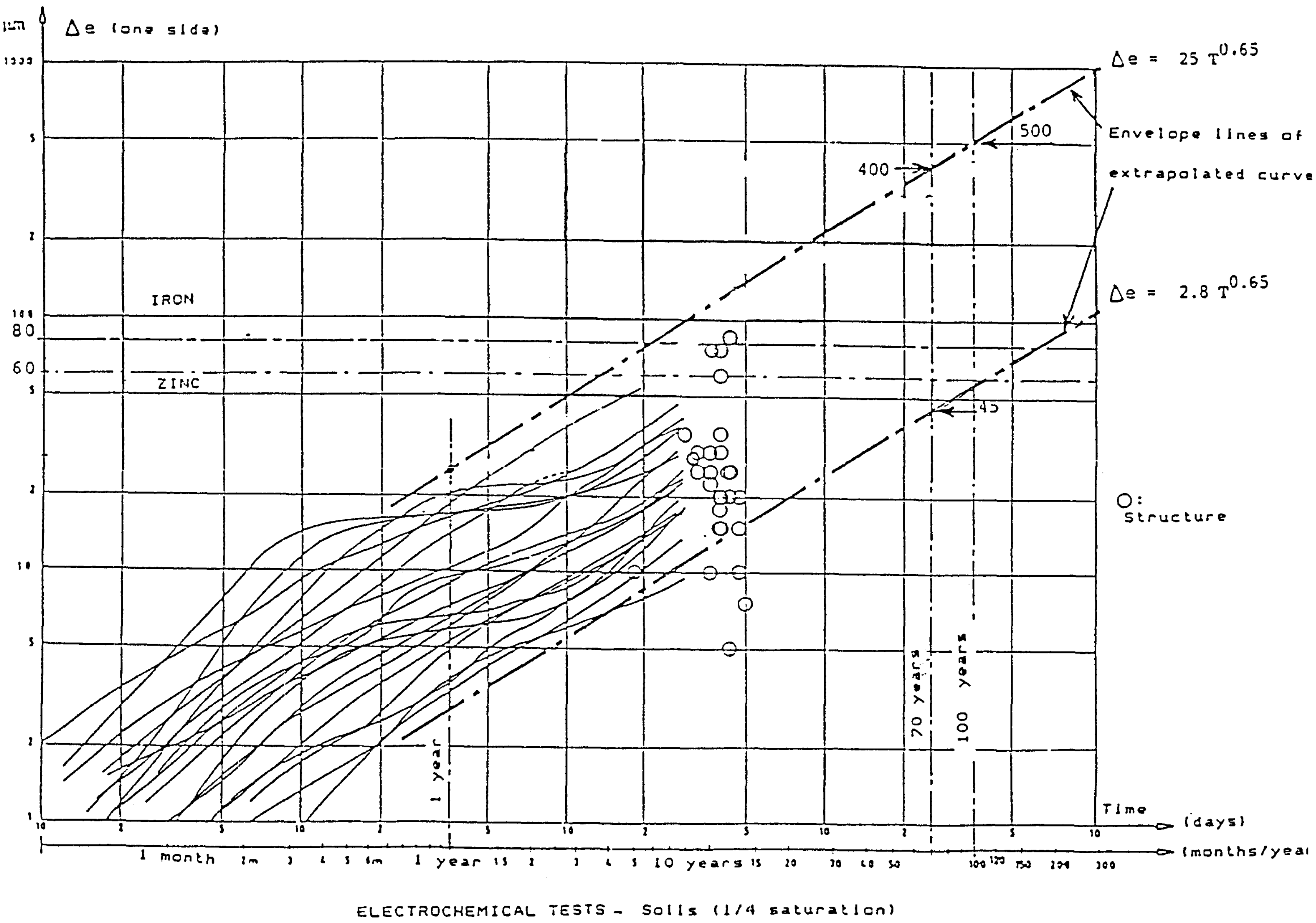
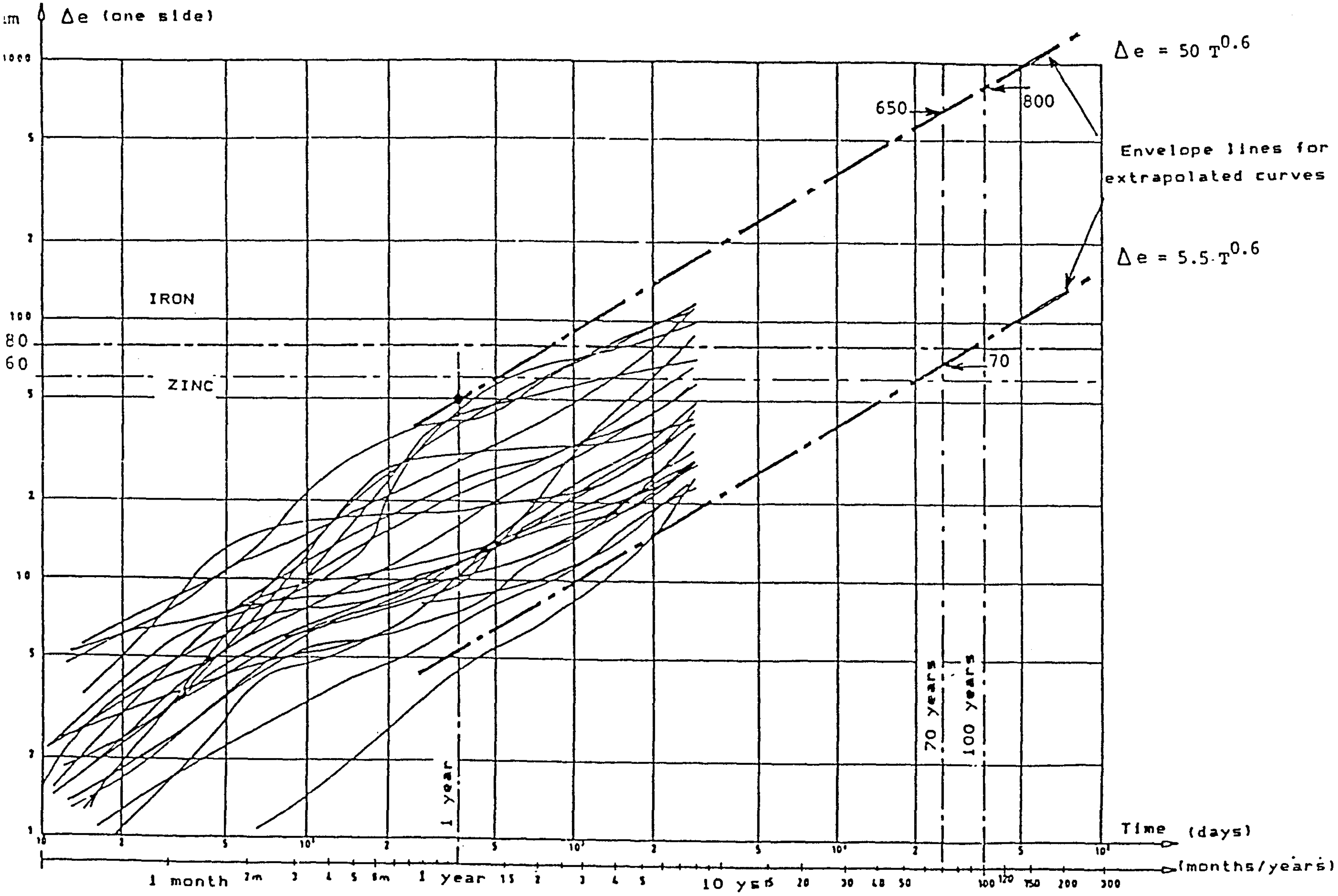


Figure 2. Summary of electrochemical cell tests at 25% saturation (7)



ELECTROCHEMICAL TESTS - SATURATED AND HALF-SATURATED SOILS

Figure 3. Summary of electrochemical cell tests at 50 and 100% saturation (7)

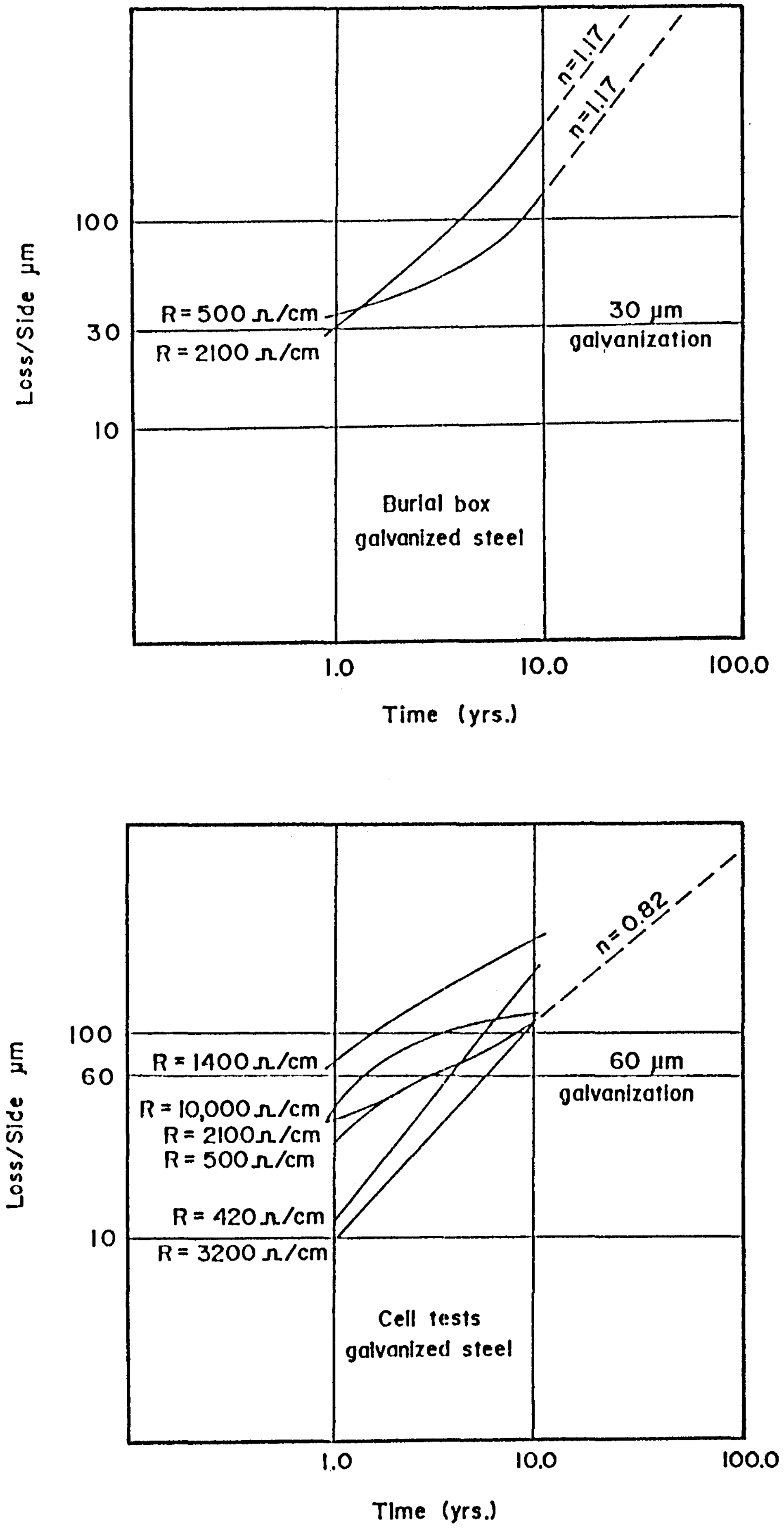


Figure 4. "n" constants, laboratory tests (galvanized) (7,21,22)

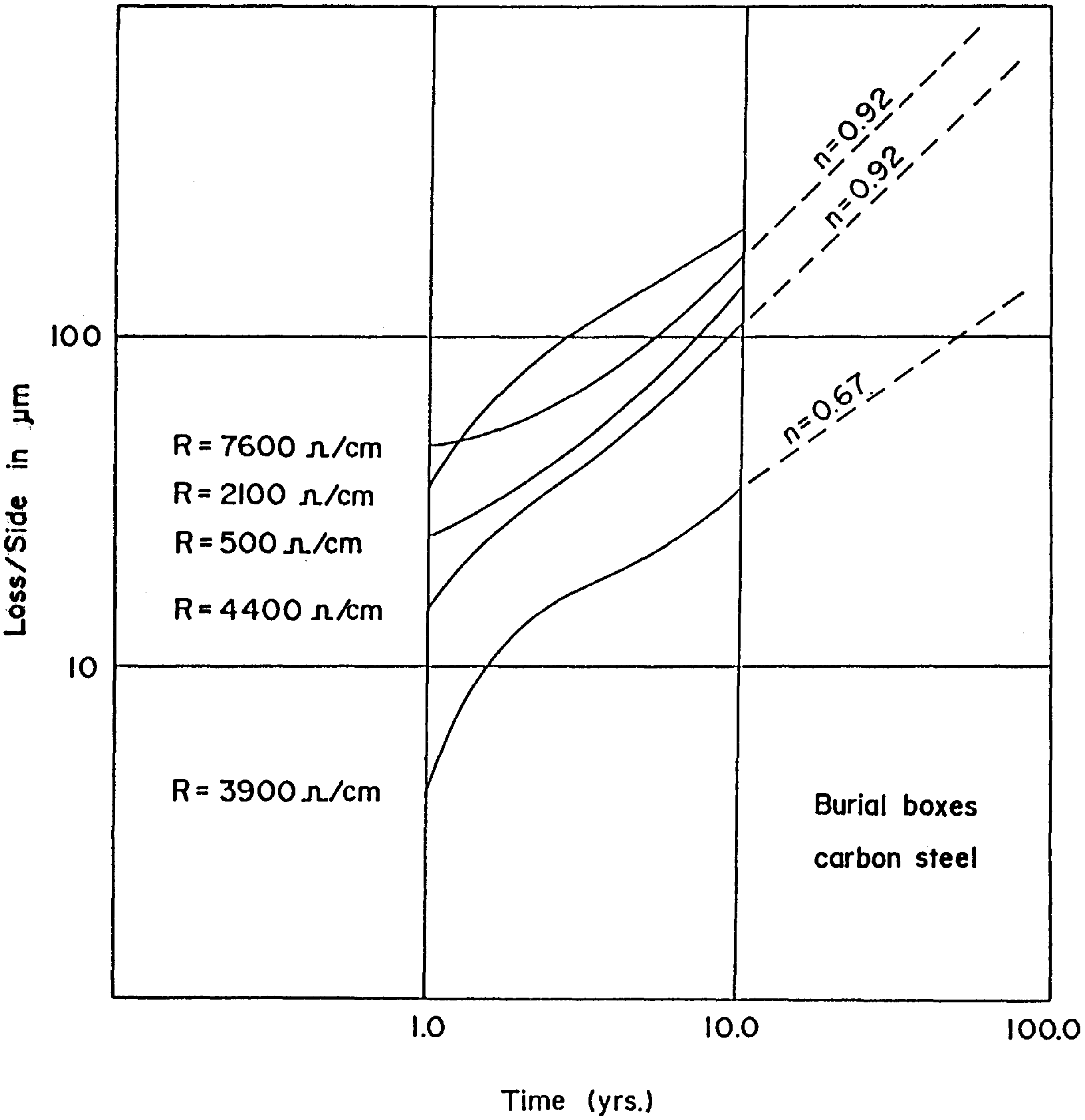


Figure 5. "n" constants, laboratory tests (carbon steel) (7,21,22)

The loss rates developed by this study are as follows:

(1) For Zinc
$V_1 = 6$ um/year (First 2 years)
$V_2 = 2$ um/year

(2) For Carbon Steel
$V_1 = 45$ um/year (First 2 years)
$V_2 = 9$ um/year

Somewhat greater losses were projected for conditions in which the backfill is saturated or with chloride or sulfate concentrations greater than threshold values. For these environments, the maximum developed loss rates were as follows:

(1) For Zinc
$V_1 = 17$ um/year (First 3 years)
$V_2 = 2$ um/year

(2) For Carbon Steel
$V_1 = 80$ um/year (First 2 years)
$V_2 = 12$ um/year

The results of these analyses can be compared to the data based on electrochemical and specimen burial data as follows:(7)

1. For non-saturated soils with resistivity greater than 3000 ohm/cm, below threshold values of chlorides or sulfates, extrapolated to 70 years.

Maximum Rates
um/year/side

	CNRS/LCPC Electrochemical	CNRS/LCPC Buried Boxes	Stuttgart
Zinc Corrosion first 2 years	12	27	6
Zinc Corrosion continuing	4	4	2
Carbon steel corrosion	11	14	9

2. For saturated soils with resistivities greater than 1000 ohm/cm containing chlorides, or sulfates in excess of threshold values.

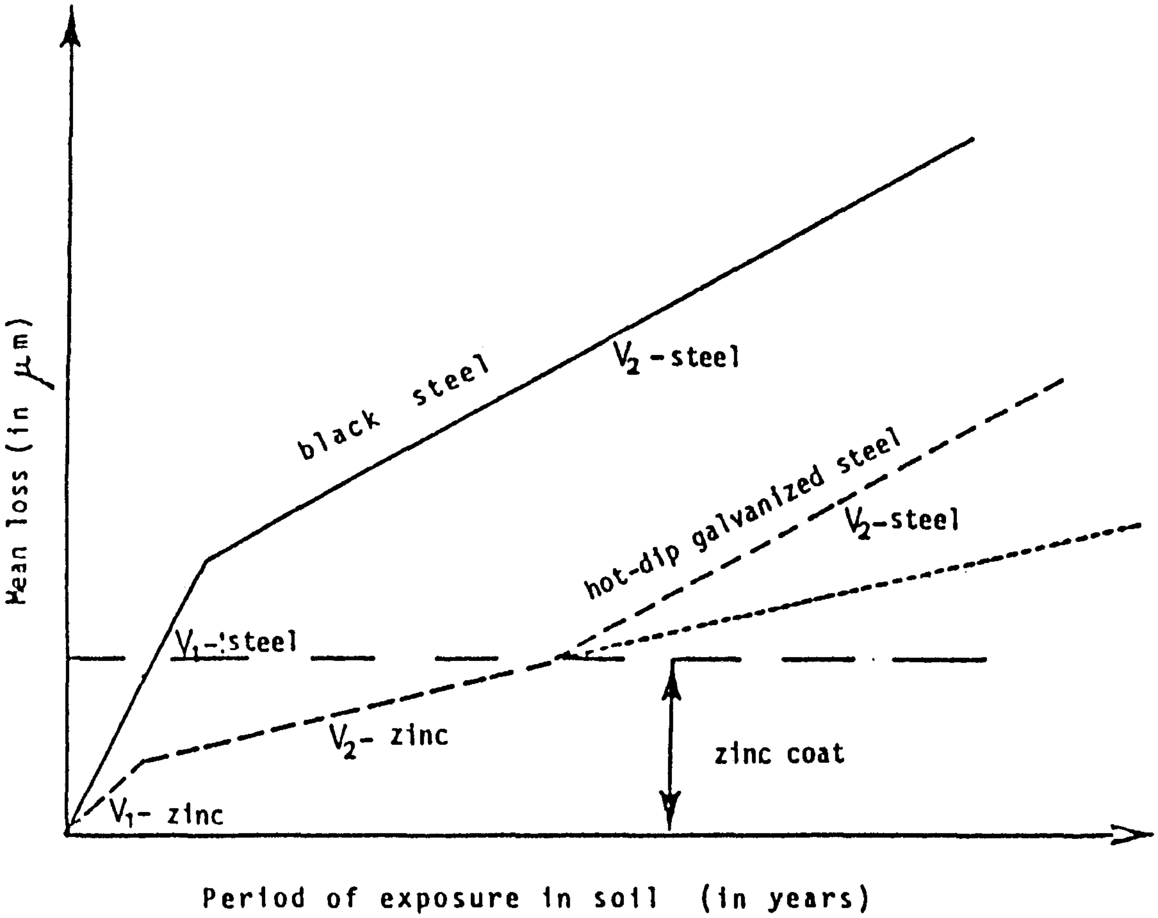


Figure 6. Idealized corrosion morphology(9)

Maximum Rates
um/year/side

	CNRS/LCPC Electrochemical	CNRS/LCPC Buried Boxes	Stuttgart
Zinc Corrosion first 2 years	30	40	17
Zinc corrosion continuing	5	--	2
Carbon steel corrosion	35	15	12

From a review of the above, it appears that the carefully controlled laboratory data both from electrochemical cells and burial boxes suggests higher maximum corrosion rates. The long term maximum carbon steel corrosion from electrochemical cells has been extrapolated from a very limited data base of samples which had reached zinc depletion at an early stage.

Other pertinent research data with special emphasis on prediction of corrosion in marine environments has been summarized by Battelle Labs.(10) This work summarizes and synthesizes results of worldwide field testing conducted in the last 50 years. It concludes that corrosion in marine environments is mainly influenced by the type of exposure, temperature, bacteria and actual chemical composition of the metal and that corrosion in the splash zone occurs up to ten times faster than in the submerged conditions. On the average, it concludes that corrosion of metals in subsoil areas is approximately one-fifth of the corrosion in the splash zone.

Based on the Battelle study, the anticipated loss rate for zinc is 2 to 4 um/year and for carbon steel on the order of 10 to 15 um/year.

A well documented recent 10 year study of corrosion of driven steel piles has been reported.(11) The study concluded that corrosion rates decrease with time. Maximum carbon steel corrosion rates averaged 80 um/year the first 2 years decreasing to 20 um/year by the 10 year with mean rates being approximately one-half. The highest rates are found in the upper 10 ft. (3 m.) zone, where oxygen would have some access to the pile. These results are generally in line with NBS data and other U.S. piling studies for corrosion rates in undisturbed soils, which are generally lower than in compacted soils.

The reported corrosion rates losses in most studies are average corrosion losses based on total weight loss over the specimen area. However, significant variation in the thickness loss occurs over any buried specimen. These local areas of greater corrosion have a significant effect on tensile strength, which cannot be directly calculated from mean corrosion loss data. This variation is clearly illustrated in figure 7 which shows the thickness variation along a 17 ft. (5.2 m.) long ribbed strip recovered from a severely corroded structure constructed in Lockport, New York. The maximum loss of thickness found at this site is roughly twice the mean loss of thickness. This general trend was true for each of the 12 strips recovered.

A particularly significant study of major corrosion failures on Reinforced Earth™ Structures constructed in South Africa has been reported.(12) The backfill utilized was a marine sand with lumps of clay containing chlorides in concentrations of 3000 to 5000 PPM partially as a result of compaction with seawater. Severe general and pitting corrosion of the reinforcements occurred leading to demolition and reconstruction after only 7.5 years of service.

The strength of the recovered strips were as low as 30 percent of initial strength with a mean of 60 percent and showed a marked loss of ductility. Using correlations between average loss of section to average loss of initial strength in a similar environment, it can be calculated that the mean corrosion loss per side was on the order of 70 um/year with a maximum of 120 um/year.(7) This case history illustrates the effect of pitting corrosion formed by differential aeration cells at locations where lumps of clay were in contact with the reinforcement. The contact between the relatively pervious sand and the steel was well oxygenated, as compared to the contact between the clay and steel which was oxygen starved. This caused the steel near the perimeter of the clay lump to become anodic and corrode over a limited area forming pits. It further illustrates that mean corrosion losses are not always good indicators of available tensile strength after significant corrosion has taken place.

(b) Summary

The generalized corrosion rate relationship developed by Romanoff has been found to be a reasonable predictive model to determine the range of corrosion rates for single phase materials. The difficulty in its implementation for galvanized steels has been in determining "K" and "n" constants which might reasonably reflect the specific environment and integrate the transition in corrosion rates between a galvanized state and the subsequent

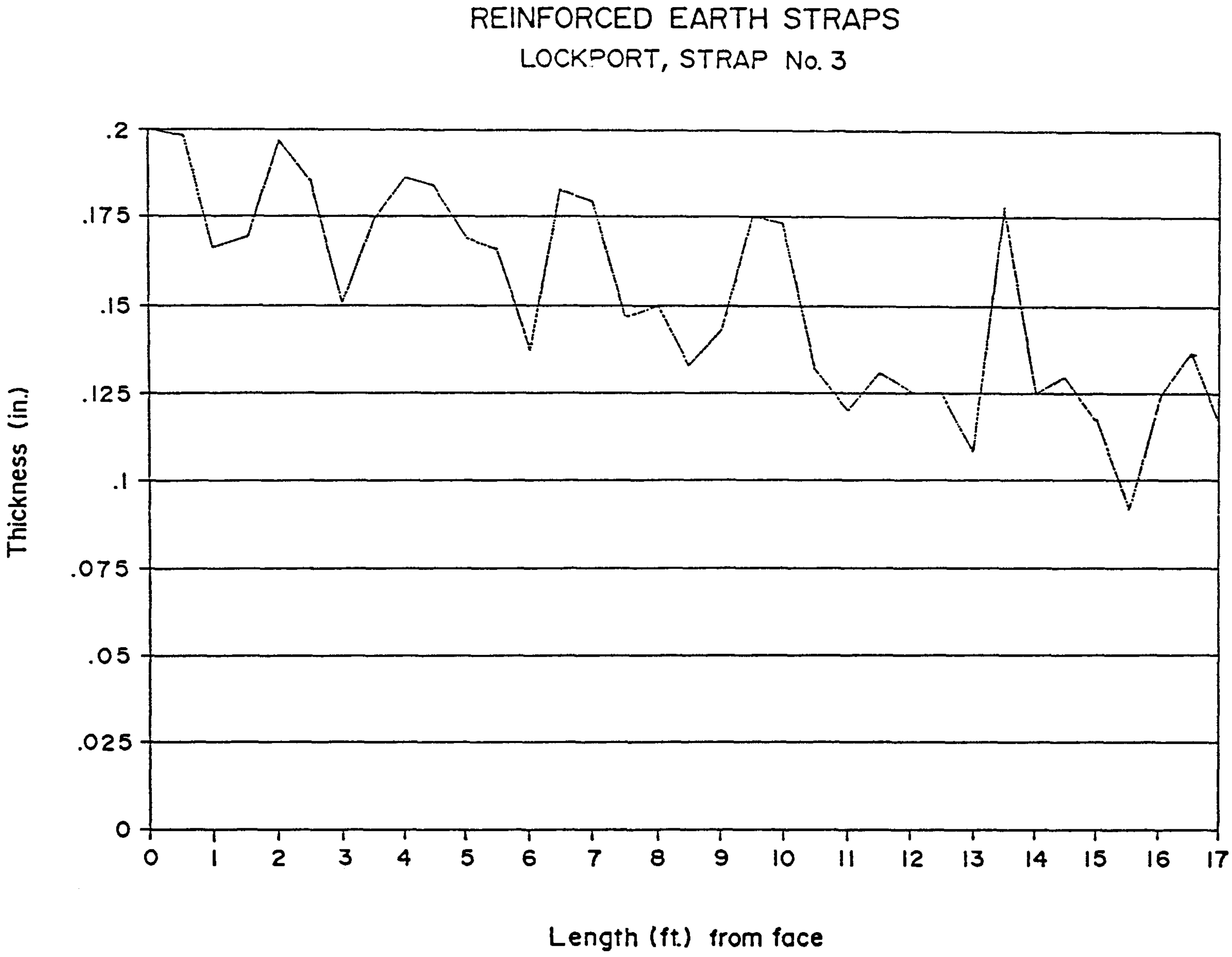


Figure 7. Measured corrosion losses along full length

bare steel phase. Such a model has not been adequately studied to date and therefore extrapolations based on limited present data cannot be adequately validated. In addition, since corrosion does not occur in a uniform manner, loss of cross-sectional area will be greater where significant pitting or greater localized corrosion occurs, than a loss computed by distributing corrosion losses uniformly over an element. The NBS data suggests that pitting depths could be significantly deeper than depths suggested by uniform loss which has been substantiated by several studies and by examination of strips recovered in Lockport, New York by NYDOT.(7,12) Pitting depths, however, are somewhat attenuated in uniform backfill environments for galvanized steel as evidenced by both NBS data, British studies and results obtained by Darbin at least in the early stages of carbon steel corrosion.

Consideration must be given to effects on tensile strength by the pitting mechanism in choosing an appropriate "K and "n" constant when using a uniform rate of corrosion model. Alternately, the effect of non-uniform corrosion losses on the tensile strength of reinforcing members may be considered statistically, based on test results which relate to the relative loss of tensile strength to relative <u>average</u> thickness loss.(7) The data developed from buried samples of reinforcements which had undergone significant corrosion losses and shown on figure 8, strongly suggests that a factor of approximately 2 exists between average thickness loss to average tensile strength loss.

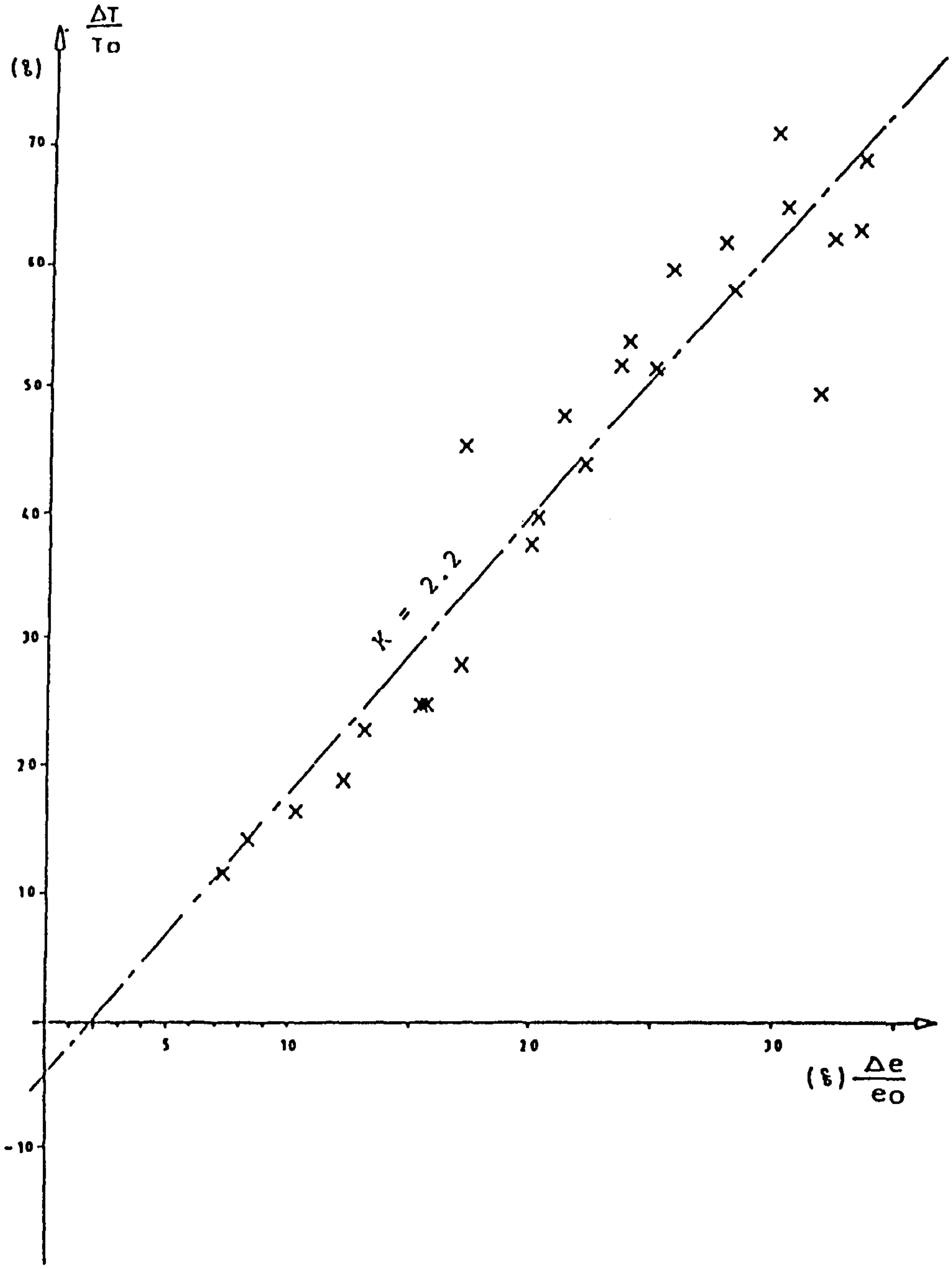
Using the NBS model, the data reviewed suggests that for galvanized steel loss determinations, using the uniform model concept, the following equation may be used:

$$X = 25\ t^{0.65} \quad \text{(Average)} \qquad (2)$$
$$X = 50\ t^{0.65} \quad \text{(Maximum)} \qquad (3)$$

For carbon steels, it appears that the expression should be modified to:

$$X = 40\ t^{0.80} \quad \text{(Average)} \qquad (4)$$
$$X = 80\ t^{0.80} \quad \text{(Maximum)} \qquad (5)$$

These relationships are generally consistent with British practice for average loss rates which considers a "K" value of 22 and an "n" value of 0.67 for galvanized steel placed in environments characterized as moderately to mildly corrosive, and for more aggressive environments, "n" and "K" values, 0.8 and 40 respectively.



PICKLED STEEL - 0.6 mm thick

SAND WITH HIGH CHLORIDE CONTENT

Figure 8. Tensile strength loss vs. thickness loss(7)

Alternately using the Stuttgart model, the following maximum rates would appear appropriate in light of the more recent data interpretation performed in connection with this study:

1)	Zinc corrosion rate first 2 years	15	um/yr.
2)	Zinc corrosion to depletion	4	um/yr.
3)	Carbon steel rate	12	um/yr.

Projections by these two methods with consideration given to a different "n" value for the appropriate phase (galvanized state, carbon steel state) are not equivalent as they have been extrapolated from different short-term data bases (less than 13 years). The Darbin constants are primarily derived from controlled electrochemical cell and laboratory burial box data, while the Stuttgart data, from selected NBS test sites which are largely uncontrolled and of equally short duration (13 years). Both sets of data have been extrapolated by considering a uniform loss model, which has been found to be inconsistent with observed behavior.

There is at present no compelling evidence to indicate which model may be more representative of actual behavior.

4. The Influence of Electrochemical or Index Parameters on Soil Parameters

The corrosion rates developed in the preceding section are consistent with backfill soils exhibiting certain minimum or maximum electrochemical or index properties generally associated with soils classified as "moderately to mildly corrosive".

The rational establishment of minimum and/or maximum limits should be a trade-off between the higher cost of more selective backfill against potentially greater metal loss associated with less selective backfill on a project basis. Unfortunately, present understanding of the very complex corrosion phenomena is rather limited as is our ability to predict environmental changes in each structure regime with time. In addition, present contracting methods for highway structures generally preclude the identification of the actual select backfill source to be used in construction, during the design phase.

Therefore, specifiers to date have adopted a philosophy of specifying minimum or maximum index properties for acceptable fills and designing the structure for maximum corrosion rates associated with these properties.

Attempts have been made by researchers to relate bulk properties of soils with their aggressiveness to buried metals. There has been however, little success in quantitatively relating these parameters to corrosion rates, although a measure of the corrosion hazard can be correlated. A notable example is AWWA Standard C 105-72 which is widely used by waterworks agencies in selecting pipe materials and protective measures.

Based on these generalized qualitative relationships found in the literature and within the range of previous experience, certain minimum or maximum limits can be inferred as reasonable starting points.

(a) Resistivity

Resistivity is the most important parameter or indicator of soil aggressiveness. With reference to resistivity, table 1 lists relationships that are generally accepted.(1)

Table 1. Effect of resistivity on corrosion

Aggressiveness	Resistivity in ohm/cm
Very corrosive	< 700
Corrosive	700 - 2,000
Moderately corrosive	2,000 - 5,000
Mildly corrosive	5,000 - 10,000
Non-corrosive	> 10,000

Based on the above, resistivity ranges in the moderately corrosive to mildly corrosive ranges are generally chosen as lower bound values. From the limited available 10 year NBS data shown on figures 9 and 10, a rough estimate can be made which suggests that corrosion rates are roughly increased by 25 percent in each successive aggressiveness range, all other conditions being roughly equal.

The corrosion rates outlined in the preceding section are associated with lower bound resistivity consistent with a "moderately corrosive" environment. Lower limits on the order of one-half this resistivity might be associated with corrosion rates roughly 25 percent greater and limits greater than 10,000 ohm/cm with potentially a 25 percent reduction, all other conditions being roughly equal.

(b) pH

Uhlig indicated that for bare steel within the range of about pH 4 to 10, the corrosion rate is independent of pH and depends only

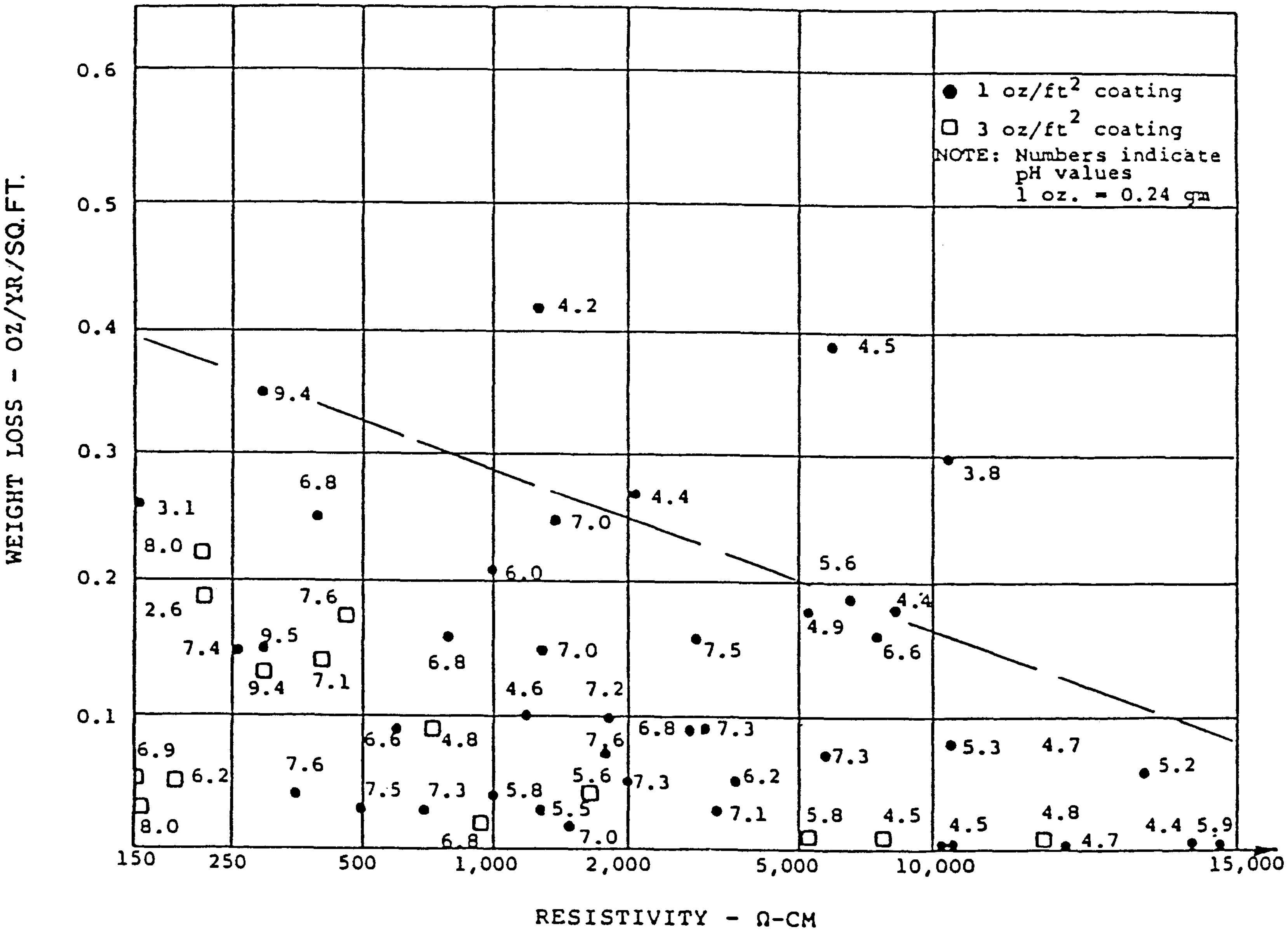


Figure 9. Metal loss as a function of resistivities (galvanized steel)(24)

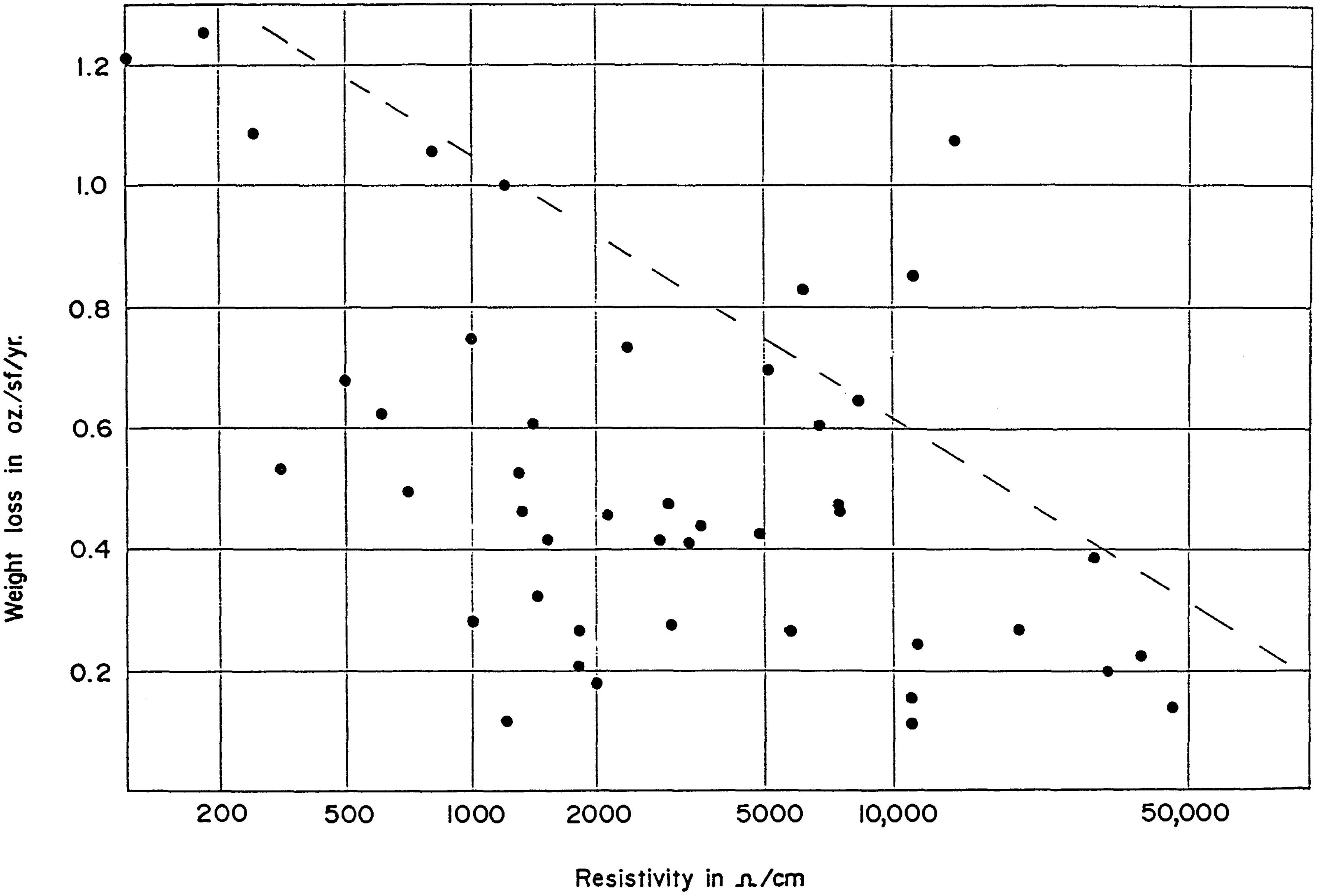


Figure 10. Metal loss vs. resistivity for carbon steel from NBS data

on how rapidly oxygen diffuses on the metal surface. In general, field retrieval tests conducted by NBS and some State Transportation agencies corroborate this conclusion, although some agencies have found that locally, pH is a good indicator of corrosiveness.

Corrosion data suggest that resistivity tends to be higher in acid soils than alkaline soils. This effect is associated with moisture content, as highly buffered neutral and alkaline soils generally contain a significant clay fraction. This will tend to lead to a higher moisture content, the presence of which will reduce the resistivity of the soil.

Soils that are extremely acidic (less than 4.0) or very strongly alkaline (greater than 10) are generally associated with significant corrosion rates. In addition, zinc is strongly attacked in strongly acidic and alkaline soils. Therefore, the galvanized coating in these regimes will have a significantly lower life expectancy.

A reasonable allowable pH range may therefore be inferred as being greater than 4.5 and less than 9.5.

(c) Water Content

With reference to water content, the data strongly suggests that maximum corrosion rates occur at saturations of 60 to 85 percent as shown on figure 11. This range of saturation for granular materials roughly corresponds to the range of moisture content required in the field to achieve the required compaction.

A recent survey of 14 California sites found saturation levels in MSE fills to be between 30 and 95 percent with most samples estimated to exceed 65 percent.(13) It appears therefore that the placement compaction requirements of soil reinforced structures are such that they will be subject to the maximum corrosion rates consistent with all other electrochemical criteria.

(d) Redox Potential

Oxidation reduction potential, referred to as redox potential has been used as a primary indicator of anaerobic bacterial corrosion. This type of corrosion with reference to soil reinforced structures is significant with fills containing organic matter normally associated with dredged fills or coastal marine sediments. Documented cases of bacterial corrosion in soil reinforcing applications exist, although rarely, and generally associated with the use of dredged fills.

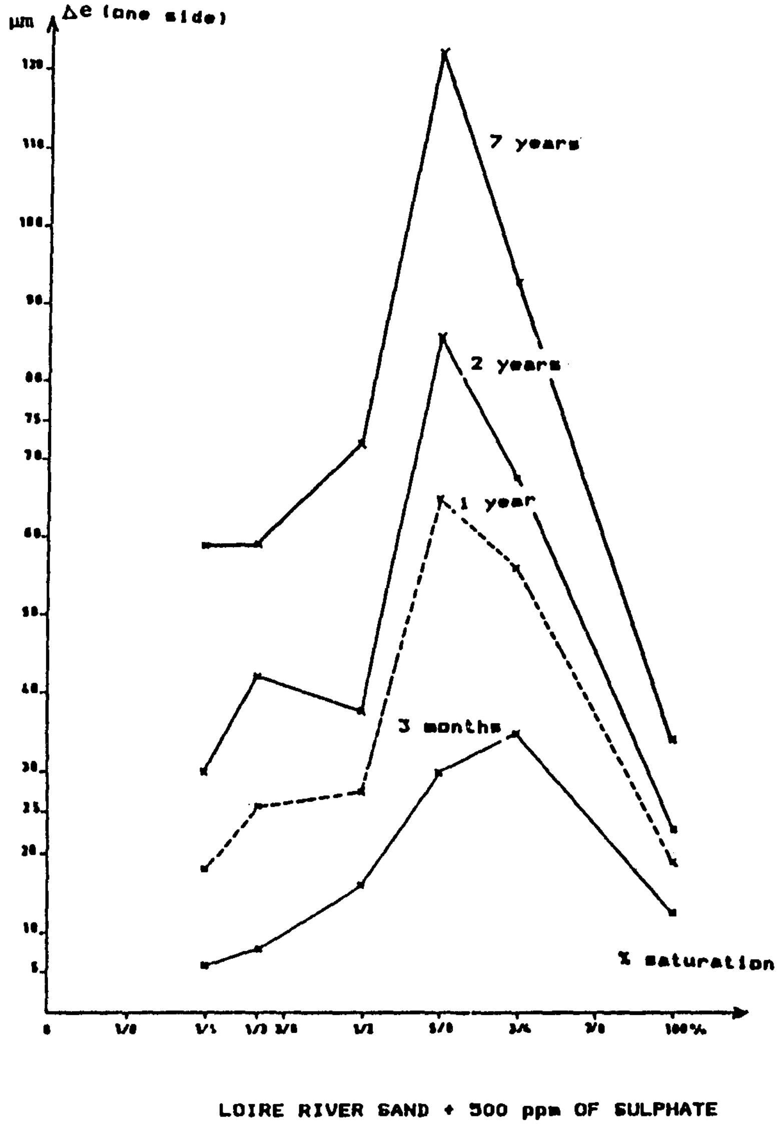


Figure 11. Effect of saturation on corrosion loss(7)

The relationships shown on table 2 corrected to a pH of 7 with a normal hydrogen electrode are generally accepted.(1)

Table 2. Effect of redox potential on corrosion

Aggressiveness	Redox Potential in mV
Severe	Below 100
Moderate	100 - 200
Slight	200 - 400
Non-Corrosive	Above 400

On this basis, redox potentials in excess of 200 mV should be considered for acceptance.

Alternately, the presence or absence of sulfate reducing bacteria can be determined by the use of "test kits" recently made available commercially in the U.S.

(e) Soluble Salts

Chlorides, sulfates and other dissolved salts decrease resistivity, promoting the flow of corrosion currents thereby disrupting or impeding the formation of protective layers. The effect of chlorides and sulfates on resistivity is shown on figure 12 for both theoretical considerations and controlled laboratory tests.(9,22)

From this data, it can be inferred that soils in the moderately corrosive range (5000-2000 ohm/cm resistivity) would be limited to a range of 60 to 180 PPM for chloride ions or 90 to 280 PPM for sulfates. Where other soluble salts are present, or a combination of chloride and sulfates, these concentrations would be reduced.

Analysis of electrochemical and burial box tests conducted in France, at 50 percent saturation levels, indicate that chlorides are more corrosive than sulfates at equal concentrations.(22) Average losses beyond the zinc consumption stage at the 10 year interval are shown on figure 13. From this data it can be inferred that at concentrations of approximately 100 PPM of chlorides and 200 PPM sulfates, corrosion losses are approximately equal to maximum loss rates previously outlined. Therefore, these concentrations could be considered upper limits, beyond which the maximum rates outlined should not be considered valid. Limited 1 year electrochemical cell tests conducted under the study generally support these conclusions.

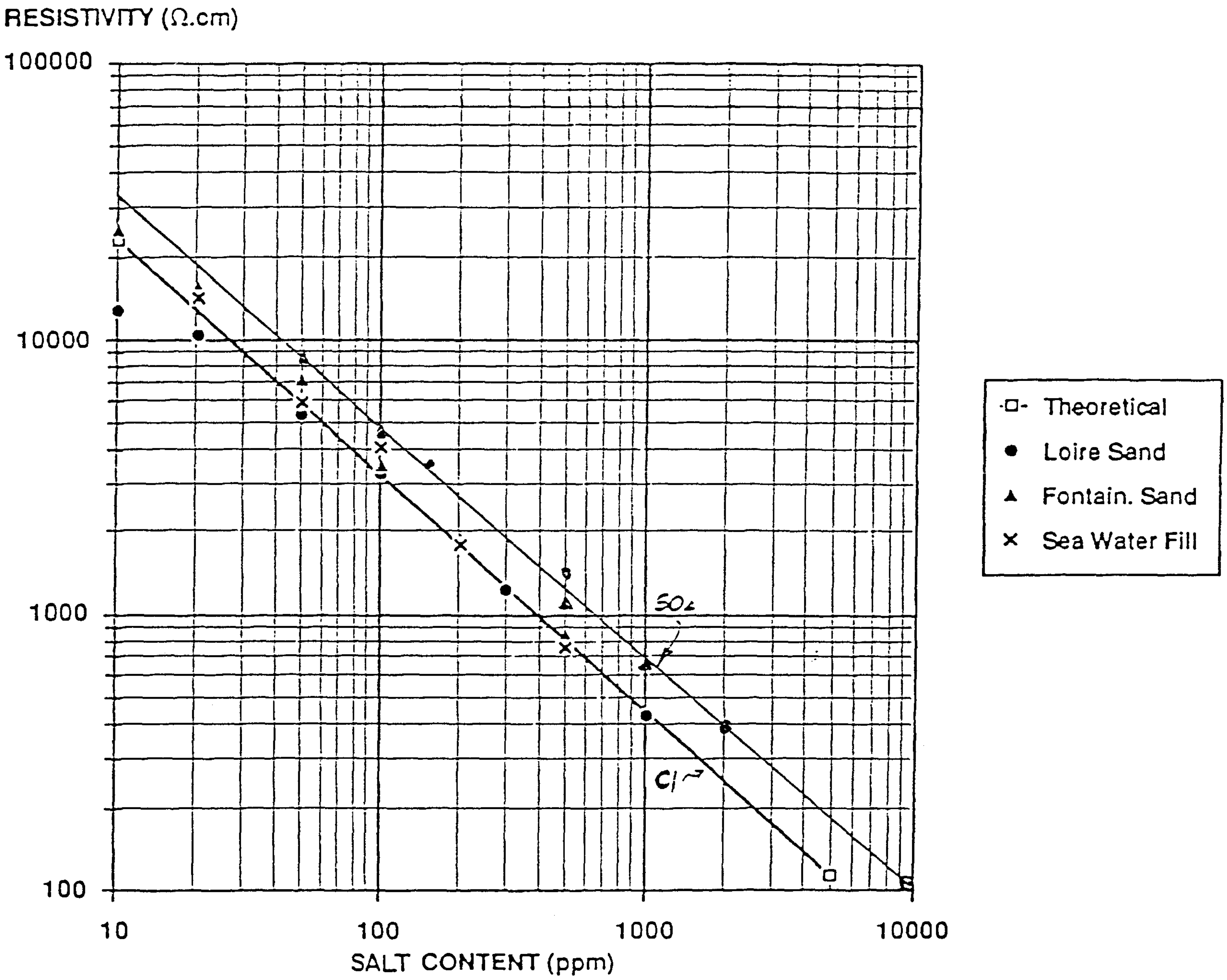


Figure 12. Resistivity vs soluble salts(9,22)

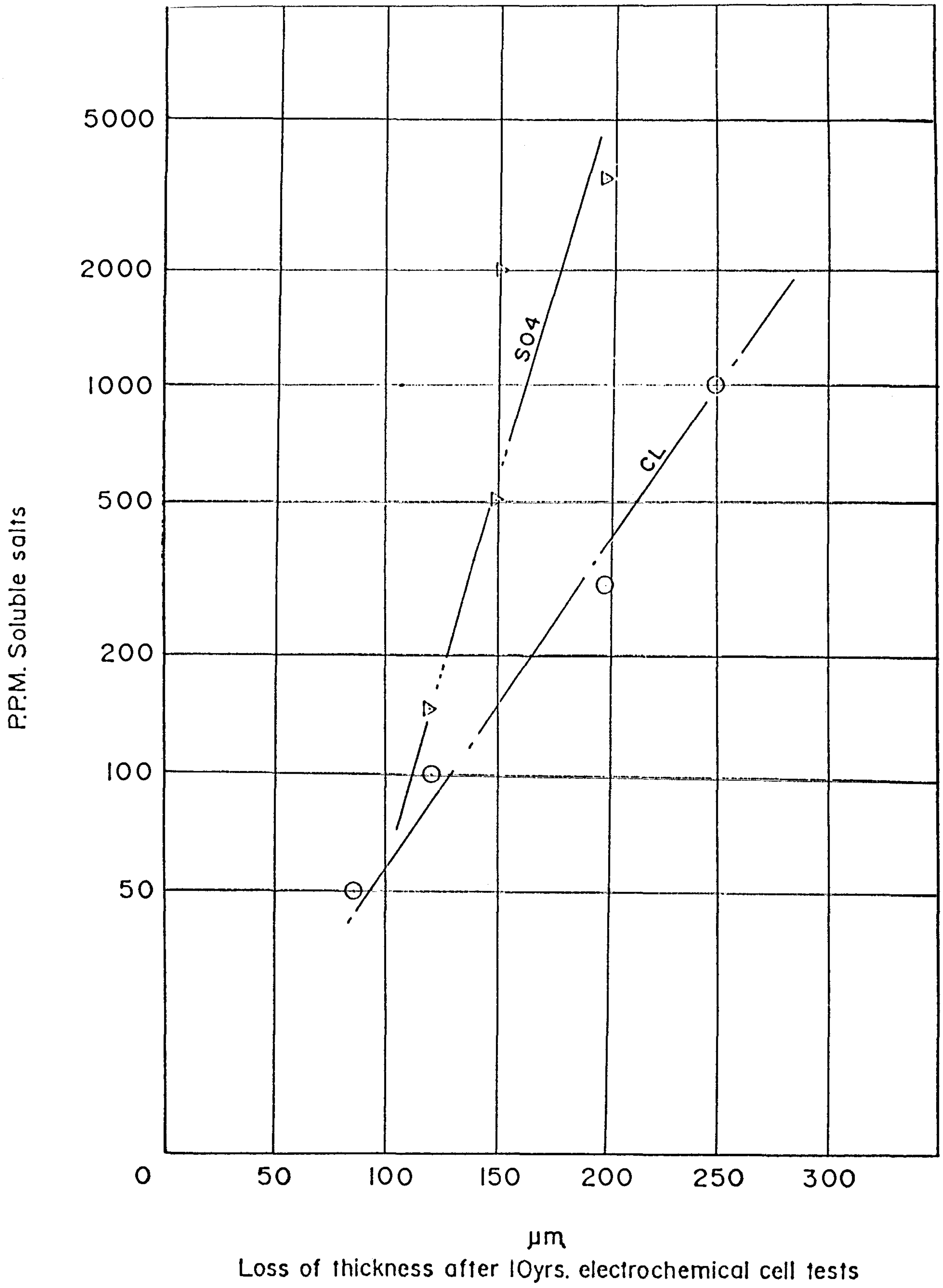


Figure 13. Metal loss vs. soluble salts 10 yrs

5. Design Philosophy

(a) Present Practice

The present design philosophy for permanent soil reinforced structures requires that (1) the reinforcement be placed in a select granular soil whose electrochemical properties exceed certain mandated limits generally associated with mildly corrosive regimes; (2) the design is predicated on a required service life generally in the range of 70 to 120 years and (3) a sacrificial thickness is added to the design thickness required, which corresponds to the mass presumed to be affected by corrosion at the end of the required service life.

Design practice (1986) in the United States, France, United Kingdom and Germany vary with respect to each of these points, yet they all agree on the general philosophy. They may be compared in tables 3,4 and 5 as follows:

Table 3. **Electrochemical limits for select backfills used in conjunction with galvanized steel reinforcements**

Property	U.S. (FHWA)	France	U.K.	Germany
Resistivity ohm/cm	>3,000	>1,000 dry⁽¹⁾ >3,000 wet⁽²⁾	>5,000⁽³⁾	>3,000
pH	>5<10	>5<10	>6 <9	>5 <9
Chloride Content PPM	<200	<200 dry <100 wet	<500	<50
Sulfate Content PPM	<1,000	<500 wet <1,000 dry	<500	<500
Sulphides PPM	--	<300 dry <100 wet	--	--
Organic Content	--	100 PPM	--	--
Biochemical Need of oxygen	--	Minimal	--	--
Redox Potential + mV	--	--	200-400	100-200

(1) dry is upland structure.

(2) wet is structure repeatedly or permanently submerged.

(3) measured in-situ

Table 4. Required design life for reinforced soil structures

Structure Classification	U.S.*	France	U.K.	Germany
Temporary Structure	--	30	--	--
Provisional Structure	--	5	--	--
Permanent Structure	75	70	120	70
Abutment & Rail Supporting Structures	100	100	120	100

* 1990 Recommendations, Task Force 27, AASHTO - AGC-ARTBA.(53)

Table 5. **Required sacrificial thickness for galvanized steel reinforcement in select backfill.**

Structure Classification	Total Sacrificial Thickness mm U.S.	 France	 U.K.	 Germany
Provisional Structures	--	0	--	--
Temporary Structures	--	0.5 dry 1.5 wet	--	--
Permanent Structures	0.65	1.0 dry	1.5	1.0
Abutments & Rail Structure	0.65	1.5 dry 2.0 wet	1.5	1.7
Marine Structures	1.2	7.0	1.5	1.7

Minimum galvanization thickness in the U.S. and France is 86 um/side and in the U.K. and Germany, 100 um/side. The sacrificial thicknesses in U.S. practice have been computed in accordance with methods outlined in the FHWA Geotechnical Notebook.(47) In French practice, marine structures are constructed with plain carbon steel.

Review of these current practices indicate that the French, German and U.K. practice is considerably more conservative than current U.S. practice, (1986) when the data is normalized with respect to a common design life.

(b) Recommended Practice

The recommended design procedure based on a synthesis of this research effort, is consistent with the philosophy presently in effect worldwide. It considers minimum or maximum mandated electrochemical limits for the backfill and the addition of a sacrificial thickness to the required structural reinforcement thickness.

(1) Recommended Electrochemical Limits

Property	Standard	Test Procedures
Resistivity ohm/cm.	>5000	ASTM G-57-78(Lab.)
pH	>4.5 <9.5	Soil Survey 8Cla
Organic Content	0.01%	AASHTO T-267-86

Soils with resistivities of less than 5000 ohm/cm but greater than 2000 ohm/cm. may be accepted if they meet the following additional requirements:

Property	Limits	Test Procedures
Chlorides	< 100 PPM	ASTM D-512, ASTM D-4327
Sulfates	< 200 PPM	ASTM D-516(B), ASTM D-4327

Because of significant variability of backfill sources, multiple samples must be tested to assess mean conditions.

(2) Required Design Life

For the purpose of determining sacrificial metal required, the following design life is recommended, pursuant to recommendations of Task Force 27 of AASHTO-AGC-ARTBA.(53)

Structure Classification	Design Life (yrs.)
Permanent Structure	75
Abutments	100
Rail Supporting Structures	100
Marine Structures	75

(3) Sacrificial Thickness Requirement

For structures constructed with carefully selected and tested backfills to ensure full compliance with the electrochemical requirements, the maximum mass presumed to be lost per side due to corrosion at the end of the required service life may be computed by assuming a uniform loss model which considers the following loss rates:

(a)	Zinc corrosion rate first for 2 years	15 um/yr.
(b)	Zinc corrosion to depletion	4 um/yr.
(c)	Carbon steel rate	12 um/yr.

The resulting sacrificial thickness for a 75 year life based on initial galvanization of 2 oz./ft.^{2}(86 um) is approximately 1.5 mm. of total sacrificial thickness. Since this is a <u>maximum</u> loss rate, it is presently assumed that the reduced minimum thickness remains proportional to tensile strength and therefore no further reduction is necessary.

The use of equation 3 to determine the maximum loss rate would yield a generally equivalent result, although it is uncertain as to whether it models an appropriate behavior.

CHAPTER 3 CORROSION MEASUREMENT TECHNIQUES

1. General

One of the primary objectives of this program is to develop remote monitoring techniques to assess corrosion rates as an adjunct to design and to provide on-line data to assess the integrity of soil reinforced structures. The techniques developed are electrochemical in nature and can be utilized for both existing structures and new construction. Prototype devices to perform these measurements have been developed and are available for general use.

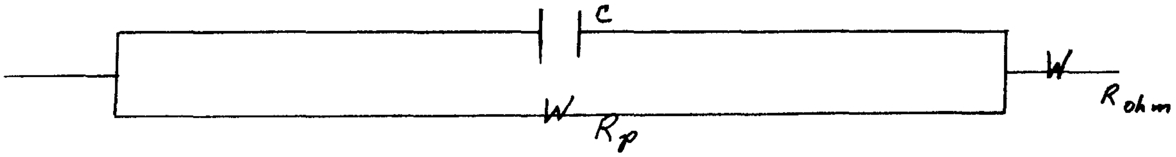
2. Corrosion Fundamentals and Polarization Resistance

Corrosion is an electrochemical process. In underground corrosion of steel, the electrochemical reaction responsible for corrosion is the oxidation of iron from the steel;

$$\mathrm{Fe} > \mathrm{Fe}^{+2} + 2^{-e} \qquad (6)$$

Because it is an electrochemical process, there is a current (flow of electrons) associated with it. Numerous methods exist to measure the current or the rate of corrosion. If the current is properly measured and the area of the specimen involved in the reaction is known, the local corrosion rate can be calculated directly.

The specimen surface involved in the corrosion process can be represented by the following equivalent circuit:



where R_p is the resistance of the surface to the corrosion process, C is the capacitance of the surface (always present at electrochemical interfaces) and R_{ohm} is the electrolyte or soil resistance.

If the electrochemical potential of the specimen is shifted, a slight amount (less than 0.02V) from its rest (or corrosion) potential by the use of a power supply and a remote electrode, then the current necessary to cause the shift can be measured and the value of R_p per unit area can be calculated. When normalized for area, which involves multiplying the measured polarization resistance by the electrode area, the polarization resistance of the material (R_P) results and has the units of ohm cm^2.

The classic description of the relation between R_p and corrosion rate was derived by Stern and Geary and is a modification of the fundamental equation for electrochemical kinetics, the Butler-Volmer Equation.(14,16) The classic equation of Stern and Geary is:

$$i_{CORR} = B_A\ B_C\ /\ [2.3\ (B_A + B_C)\ R_P] \qquad (7)$$

Where i_{CORR} is the corrosion current density of the surface of the specimen, and B_A and B_C are the anodic and the cathodic Tafel slopes respectively. A Tafel slope is the rate of change of voltage (in volts) per decade of current on a log current density basis as the voltage of the specimen is shifted away from its rest or corrosion potential. The anodic Tafel slope is the value of that change as the potential is shifted in the electropositive direction. The cathodic Tafel slope is identical except for electronegative polarization, or in the less corroding direction. These Tafel slope values can be determined by experiments or estimated from literature data for soil corrosion. Further, because the expression involves the product of the two divided by the sum, and because Tafel slopes are typically limited to a relatively small range, the calculation of corrosion rate (corrosion current density) is not highly effected by errors in the values of the Tafel slopes. The term:

$$B_A\ B_C\ /\ [2.3\ (B_A + B_C)]$$

typically varies between 0.08 and 0.02 volts and is hereafter referred to as the <u>conversion constant.</u>

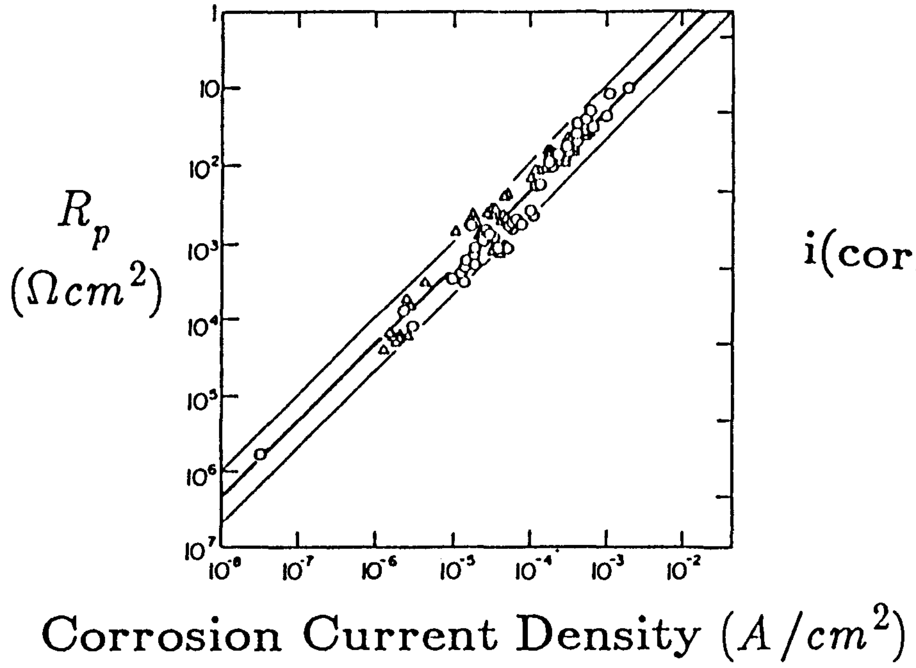
Stern and Wisert showed that the corrosion rate calculated from Rp correlated well with actual corrosion rates determined from weight loss measurements for a variety of steels in aqueous environments.(16) The relationship for converting the conventional mpy corrosion rate to corrosion current density for steel is:

$$mpy = i_{CORR}\ /\ 2.2 \qquad (8)$$

where i_{CORR} is expressed in uA/cm^2.

One complication in using polarization resistance measurements is that the resistance that is measured in a direct current or low frequency measurement is the sum of R_P and R_{ohm}. The value

Iron and Steels in Acidic and Neutral pH Electrolytes



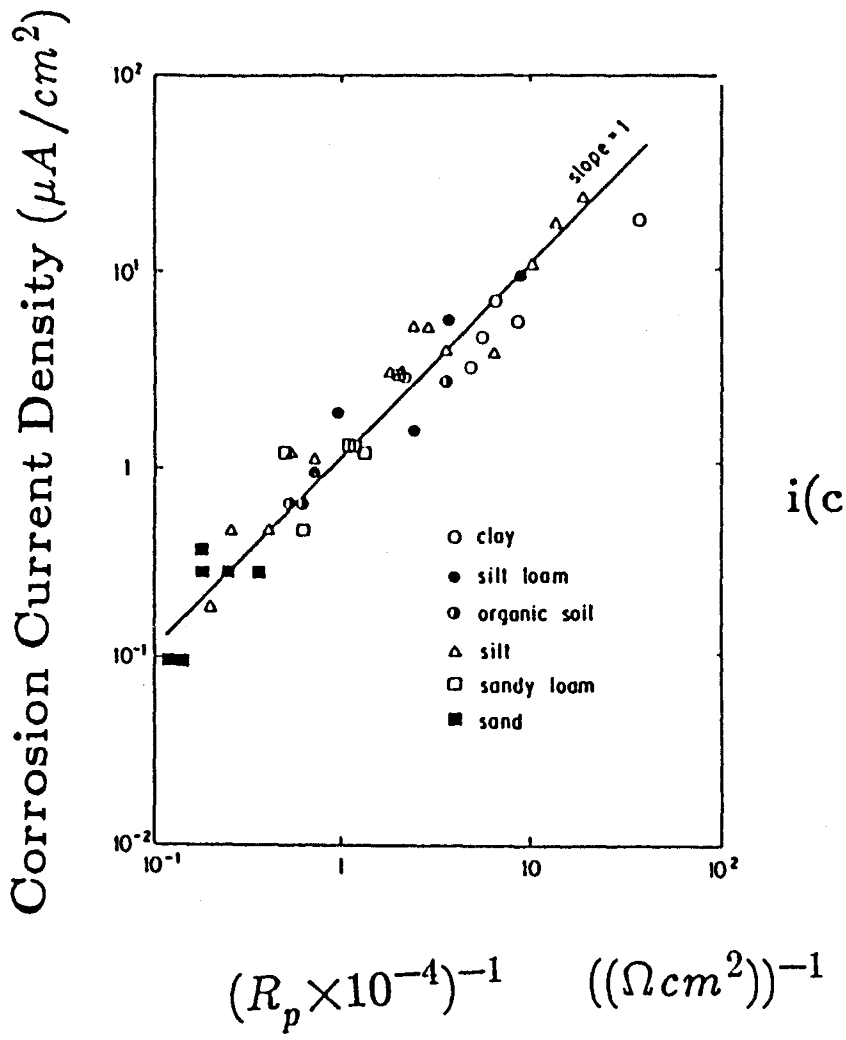
$$i(\text{corr}) = 0.021/R_p$$

Haruyama and Tsuru

ASTM-STP727,167(1981)

Figure 14. Polarization resistance vs. current density

Steels in Soil



$$i(\mathrm{corr}) = 0.0112/R_p$$

Kashara and Kajiyama

Corrosion, 39, 475(1983)

Figure 15. Polarization resistance vs. current density (steels in soils)

of R_{ohm} is generally much smaller than R_p in conductive solutions. But in low conductivity solutions as in many soils, the value of R_p must be measured independent of the influence of R_{ohm} or must be corrected for in the DC measurement in order to properly determine the corrosion rate from the polarization resistance, that is, the value of the polarization resistance typically measured by a DC technique is:

$$PR = R_{ohm} + R_p \qquad (9)$$

For soil environments some method of measuring or otherwise removing R_{ohm} is required.

Electrochemical impedance spectroscopy (EIS) or AC Impedance is a fairly new electrochemical technique which determines the values of R_p, R_{ohm}, and C in the equivalent circuit.

Haruyama and Tsuru used EIS methods to determine corrosion rates corrected for errors introduced by R_{ohm} (which cause underestimation of the actual corrosion rates) for steels in aqueous environments, some of which were low conductivity, and compared them with actual weight loss.(17) Figure 14 shows the excellent correlation obtained.

Scully extended EIS methods to soil and showed excellent agreement between predicted and actual weight loss corrosion rates for steel specimens in two different soil types for up to 6 months of exposure.(18,19)

Tokyo Gas used EIS methods to measure corrosion rates of steel in 40 different soils for about 1 year exposure and showed excellent agreement between measured and actual corrosion rates as seen in figure 15.(20) The University of Manchester (UMIST) has demonstrated the relevance of EIS methods in measuring corrosion rates in soil reinforced structures in the United Kingdom.

At laboratory scale, Montuelle reported research on galvanized steel specimens allowed to corrode in a special cell.(21) Weight loss data and corrosion rate determined by polarization resistance measurements are reported and compared for up to 17 months of exposure. Good agreement between the electrochemical method and the actual weight loss is reported.

Darbin reported further data on 24 soil types at several moisture levels over a 6-year period extending the validity of the initial study.(7) A 5 year comparison of actual loss by corrosion to that predicted by polarization resistance is given for five soil-humidity combinations. In all cases, the agreement is within a factor of two, and in most cases the agreement is within 25 percent. This agreement is excellent in light of the fact that the reproducibility of conventional weight loss corrosion experiments is seldom better than a factor of 3.(23) The polarization resistance in these studies was determined by a slow sweep rate or low frequency (0.4 mV/second) potentiodynamic method with 10 mV peak to peak applied voltage signal. No correction for R_{ohm} was made.

An estimate of the values of R_p and R_{ohm} was made from this data utilizing a conversion constant of 0.050 volts. This conversion constant was chosen because it corresponds to the 250 mV average Tafel slopes reported by Montuelle. Values of R_p were on the order of 50,000 to 500,000 ohm cm^2 while values for R_{ohm} were on the order of 50 to 500 ohms. The specimen area in these tests was 15 $cm.^2$ and therefore R_p the <u>measured</u> polarization resistance would be about one order of magnitude lower than values given above for R_p. However, it can clearly be seen that the error due to neglecting the ohmic resistance in these tests is quite small, typically two orders of magnitude smaller than the measured polarization resistance. At field scale with higher corrosion rates the effect of ohmic resistance may be significant.

Corrosion rates determined from polarization resistance measurements require:

(a) That the exposed area of the component to be analyzed be known or estimated accurately. An accurate estimate can be made for reinforcing strips or grids in reinforced soil structures because the geometry is well defined.

(b) That the polarization resistance be determined independent of the ohmic resistance (soil resistance). This can be accomplished by use of the EIS approach to polarization resistance determination or be neglected when considerable experience has been gained on actual structures which shows it to be justified. Alternately, it can be measured separately and subtracted from the measured polarization resistance.

(c) That the value of the conversion necessary to convert the polarization resistance to corrosion rate be known. However, estimates of this constant suffice in most applications. Data from Tokyo Gas suggests a value of 0.021 volts for this constant for the case of steel corrosion underground and show it to be independent of the soil type. Pipeline companies routinely use a constant of 0.035 for steel pipe. Montuelle published data base for galvanized steel in numerous soils suggests conversion constant on the order of 0.050.(21,22) Therefore, it can be assumed that conversion constants range between 0.020 and 0.050.

(d) That the composition of the surface being analyzed be known. Early on in the life of new structures, it can clearly be assumed that the surface is galvanized. Corrosion potential monitoring can determine subsequent metal phases as the reinforcement loose zinc to an ultimate carbon steel base.

It can be concluded that the use of polarization resistance measurements in general compliance with ASTM G59-78, corrected for soil resistance by separate measurements are applicable for determination of corrosion rates of reinforcing elements in soil reinforced structures. While the conversion constants for steel and galvanized surfaces may vary (within a factor of 2), use of the 0.035 for steel and 0.050 for galvanized steel as determined from the Montuelle data should be considered where exact data for a particular soil are not known. The basis of use should be potential measurements which will distinguish surface composition.

3. Potential Measurements

The primary purpose of the potential measurements is to establish when significant portions of the structure have lost zinc coverage and steel is exposed to the soil environment. Once bare steel is exposed to the soil environment, the corrosion rate of the sacrificial zinc (galvanization) may be accelerated due to the galvanic couple with the steel. Comparisons between the potential of the reinforced structure (reinforcements) and the potentials of buried zinc and carbon steel coupons will provide the information necessary for determining when large quantities of bare steel are being exposed to the soil. If the potential of the structure is near that of the zinc coupon, then the reinforced structure remains well galvanized. As the potential of the structure becomes more positive and begins to approach that of the steel coupon, the galvanizing is being lost and more bare steel is being exposed.

The corrosion potential is the voltage of a structure or component of interest measured with respect to some suitable reference electrode. The common reference electrode in underground corrosion studies is Copper/Copper Sulfate (Cu/Cu_2SO_4). For a given material, in a given environment, the potential is an indication of the corrosion activity. The more positive the potential, the greater in general, is the cor rosion. Changing environmental conditions, especially in soils can produce many apparent exceptions to this rule. Therefore, in general, it is very difficult to predict corrosion rates from potential measurements. For a series of different alloys corroding in a particular environment, the corrosion potentials for the alloys will likely identify which alloy is present.

Potential differences were initially determined in an extensive NBS study where the potentials of zinc and steel specimens were examined in 12 different soils. The results of the potentials of the zinc and steel specimens in the NBS soils are shown on table 6 as follows:(2)

Table 6. NBS measured potentials

Soil #	Zinc Potential vs Sat. Calomel	Steel Potential vs Sat. Calomel
51	-1.02	-0.71
55	-1.02	-0.75
56	-1.04	-0.73
58	-1.04	-0.74
60	-1.02	-0.68
61	-1.02	-0.72
62	-0.92	-0.72
63	-0.94	-0.64
64	-1.08	-0.73
65	-1.01	-0.71
66	-0.94	-0.72
70	-0.99	-0.76

All potentials would be approximately 0.10 volts more negative if measured relative to the Cu/Cu_2SO_4 reference electrode rather than the saturated Calomel reference electrode shown.

The soils in table 6 were tested in the "air free" condition, minimizing the corrosion tendency. In the presence of air, it is expected that the potential would increase in the positive direction and the extent might depend on the particular soil and metal type. Therefore, under actual field conditions the voltage separation might be different than shown on table 6.

Although the corrosion potentials alone cannot determine corrosion rates, they should be useful in determining the composition of the exposed surface. When sufficient zinc had been depleted to expose the iron/zinc alloyed region (an

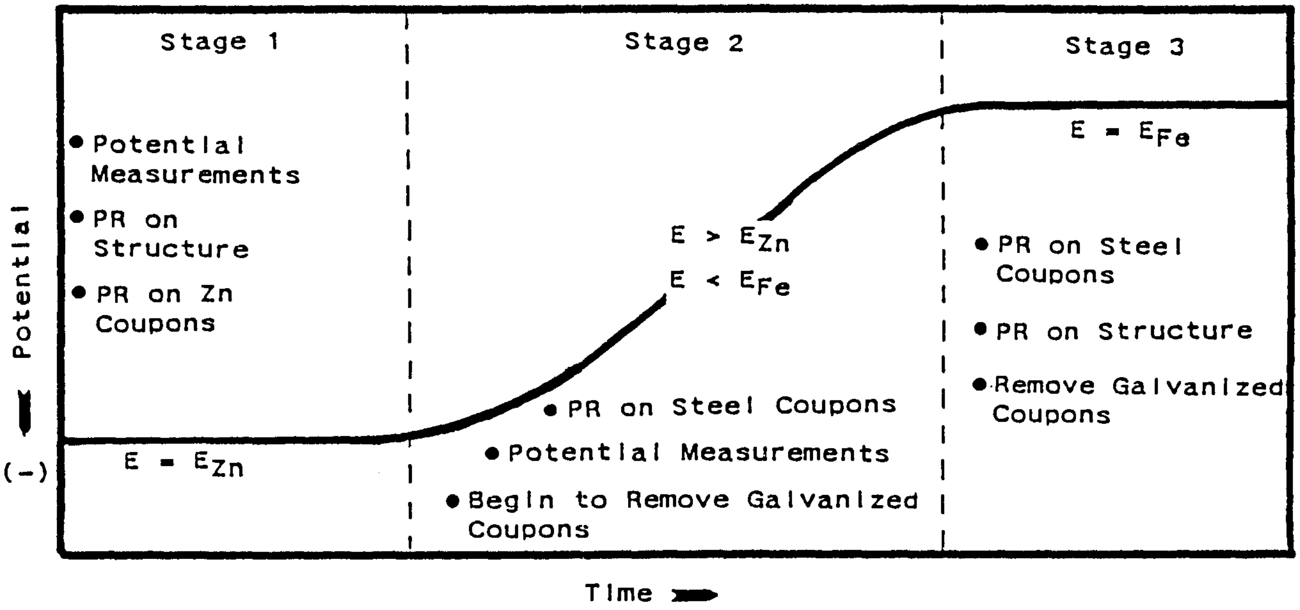


Figure 16. Stages of galvanized structure performance

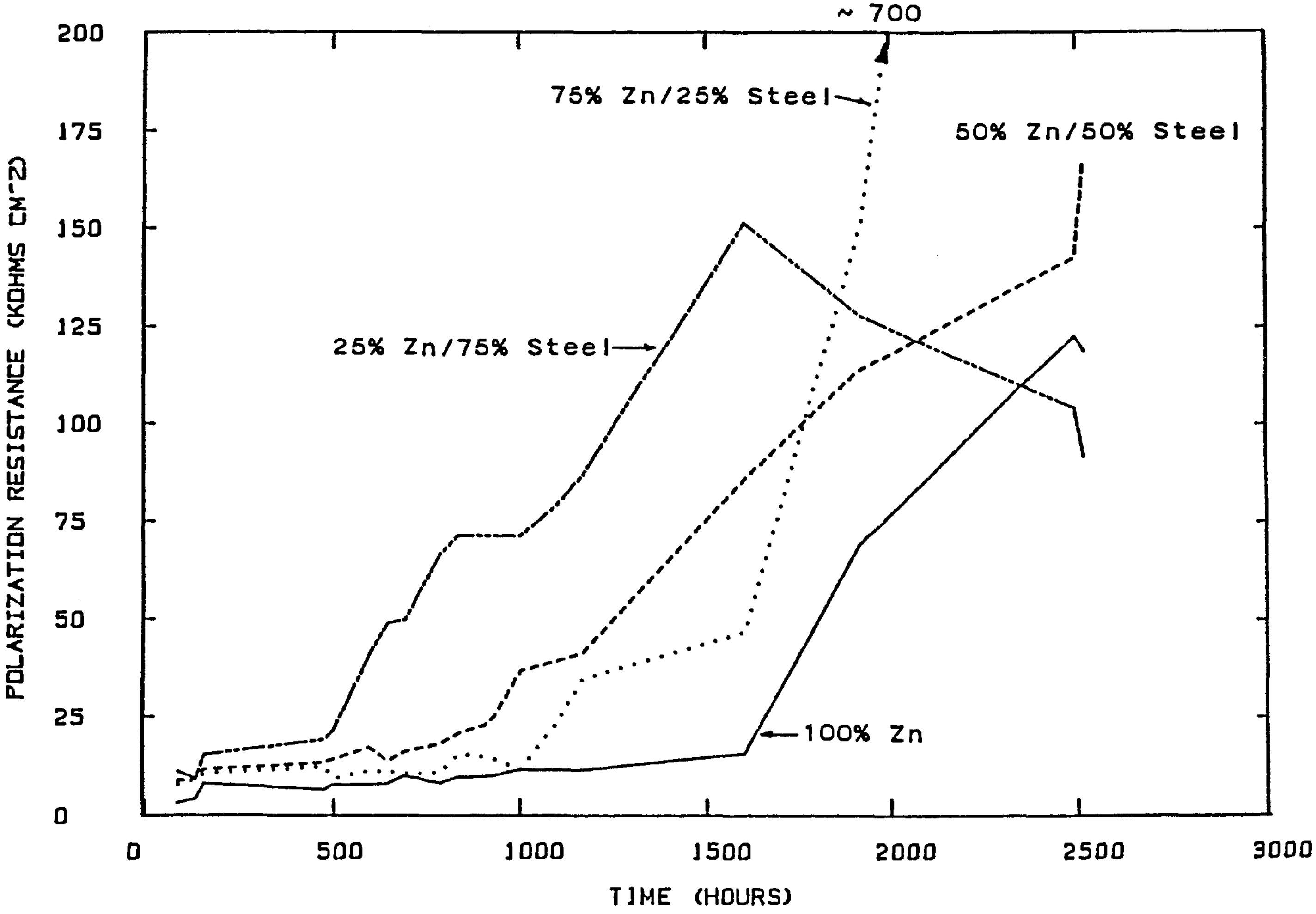


Figure 17. Polarization resistance as a function of exposure time

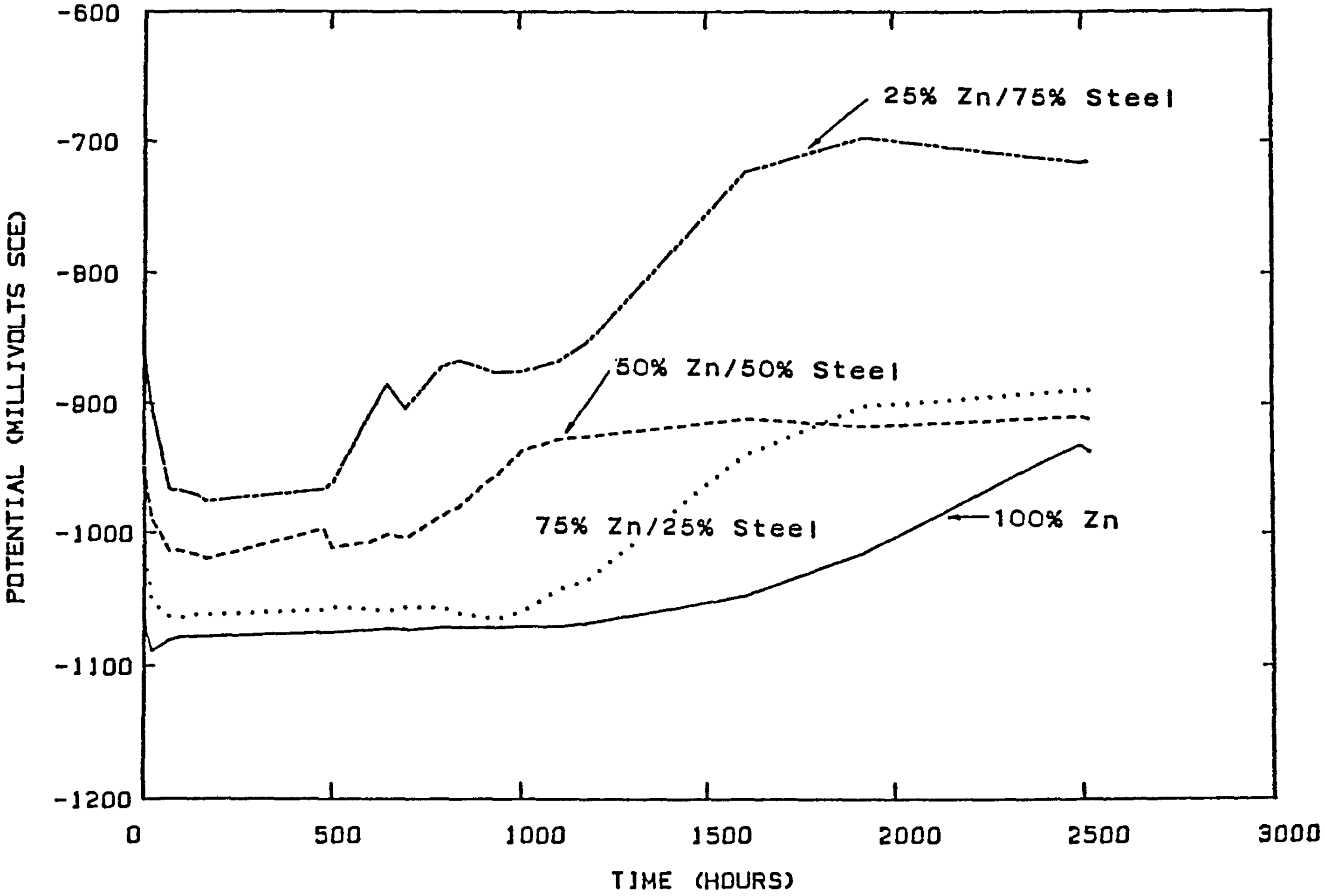


Figure 18. Free-corrosion potential as a function of exposure time

interphase between the steel and zinc which develops during galvanization process), as schematically shown on figure 16, the corrosion potential would be somewhere in between that for zinc and for iron.

These concepts have been field validated in previous measurements made on two Reinforced Earth™ Structures.(24) The potentials as expected were somewhat more positive indicating the presence of air. Potential measurements longitudinally along the reinforcement generally indicate changes in potential suggesting uneven corrosion along the reinforcement with greater corrosion activity near the face.

4. Laboratory Validation

A limited laboratory study was performed in cell tests to independently determine relative corrosion rates obtained by polarization resistance measurements and electrochemical impedance measurements.

Properties of the soil used are in table 7. Four soil cells were constructed each containing a specimen with an area of 50 cm^2. The cell-specimen configuration was such as to expose only one side of the galvanized specimen, with no edges exposed. The four conditions examined were (1) 100 percent galvanized steel, (2) 75 percent galvanized, 25 percent steel, (3) 50 percent galvanized, 50 percent steel and (4) 25 percent galvanized 75 percent steel. The different percent steel areas were produced by masking-off the desired galvanized area and dissolving the exposed zinc in an acid bath.

Table 7. Soil properties for laboratory validation

Property	Measured Value
pH	5.2
CL, ppm	63
SO_4, ppm	11
HCO_3, ppm	109
Soluble salts, ppm	304
Resistivity ohm/cm	15,600
% sand	59

Figure 17 shows values for polarization resistance (PR) as a function of exposure time for four specimens. Increasing PR values corresponds to a decrease in corrosion rates. For all specimens, the value for PR tends to increase with increasing exposure time. Typically, the increase in PR value corresponds to the observed increase in the corrosion potentials.

Electrochemical impedance measurements were made periodically during the exposure and the data evaluated using Nyquist and Bode plots. The polarization resistance values agree fairly well with values shown on figure 17 from conventional PR measurements. The polarization resistance obtained by EIS measurements is smaller by 10 percent to 25 percent which accounts for the soil resistance in the circuit.

The electrochemical impedance measurements clearly shows the multiple reactions taking place on the specimen surface. The different reactions likely correspond to (1) reactions on bare steel and (2) reactions on the galvanized surface. However, because the areas of exposed steel and Zn are unknown and because a significant amount of research would be required to provide the understanding necessary to better analyze the electrochemical impedance data, it is believed that a combination of potential and conventional PR measurements provide the most effective and economical monitoring scheme, provided soil resistance in the circuit is measured and a corrected polarization resistance is used.

The preliminary conclusion based on electrochemical cell measurements was found to be generally valid when compared to instrumented full-scale structures where corrosion rates have been measured by both methods. However, under certain field conditions, especially where PR measurements are low indicating high corrosion rates, soil resistance was found to be sufficiently high to materially affect the resulting corrosion rates by a factor of 2 or more. Therefore, it was concluded that separate measurements of soil resistance should be routinely made and the polarization resistance corrected prior to calculating a corresponding corrosion rate. This procedure is considerably simpler and as accurate as performing complete electrical impedance measurements (EIS).

This limited laboratory study was also used to examine the effect of zinc coverage on the electrochemical potential. The purpose was to obtain a first estimate of changes due to loss of galvanization in a quantitative manner. The cells were the same as the ones used previously to study corrosion rates using polarization resistance techniques.

Figure 18 shows the free-corrosion potential versus exposure time for the four specimens. During the initial exposure (0-500 hrs), the 100 percent Zn specimen had the most negative potential

(-1.08 V, SCE), while the 25 percent Zn/75 percent steel specimen had the most positive potential (-0.97 V, SCE).(1) At increasing exposure times, the potential of the 25 percent Zn/75 percent steel specimen increased up to a value similar to that of a bare steel exposed specimen (-0.7 V, SCE). This increase in potential most likely corresponds to an increase in exposed steel area due to the corrosion of the galvanized layer. The remaining specimens also showed an increase in potential as a function of time.

The laboratory data agrees with data for galvanized steel reported by NBS and others.(24) Typical potential values for a well galvanized structure would be -1.10 to -0.80 V, SCE. For bare carbon steel, the potentials are more positive and typically in the range of -0.70 to -0.40 V, SCE. Transition stages would be in between these values.

(1)E (Saturated Calomel Electrode, SCE) - 0.07V = E (Copper/Copper Sulfate Reference Electrode/Cu/Cu_2SO_4, e.g., -0.97V, SCE = 1.04V, Cu/Cu_2SO_4.

CHAPTER 4 SYSTEM DESIGN

1. General

The measurement concept to be employed for monitoring soil reinforced soil structures includes both potential measurements and polarization resistance (PR) measurements. Both measurement techniques must be performed on buried coupons, as well as the actual reinforcement members (structure). The buried coupons will include coupons made from carbon steel, zinc, and galvanized steel. Figure 16 shows the three stages of galvanized structure performance. During Stage 1, the galvanizing is intact and either no steel is exposed to the soil or the steel is well polarized and completely protected. The potential of the structure is the same as that of zinc. In Stage 2, increased steel is exposed as galvanization is lost and the potential of the structure becomes more positive and approaches that of bare steel. In Stage 3, essentially all the galvanization has been lost and the potential of the structure is the same as that of carbon steel. During the different stages, the monitoring procedures change, as summarized in figure 16.

Single steel and zinc coupons should be buried at each site, with multiple galvanized coupons. The multiple galvanized coupons can then be retrieved to help establish more fully the condition of the structure.

(a) New Structures

For new structures, three types of coupons should be buried: (1) steel, (2) zinc, and (3) galvanized. In addition, actual reinforcement members must be instrumented for measurement purposes. The three stages of structure life will be determined by comparing steel and zinc coupon potentials to those measured for the structure. During Stage 1 (structure potential = zinc coupon) the following monitoring should be performed:

- Potential measurements on each coupon and structure (reinforcement member) to establish the change from one stage of structure life to another.

- PR measurements on zinc and galvanized coupons and on the structure to estimate rate of zinc corrosion (zinc loss).

- PR measurements on carbon steel coupons to characterize changes in the corrosion rate throughout the structure life.

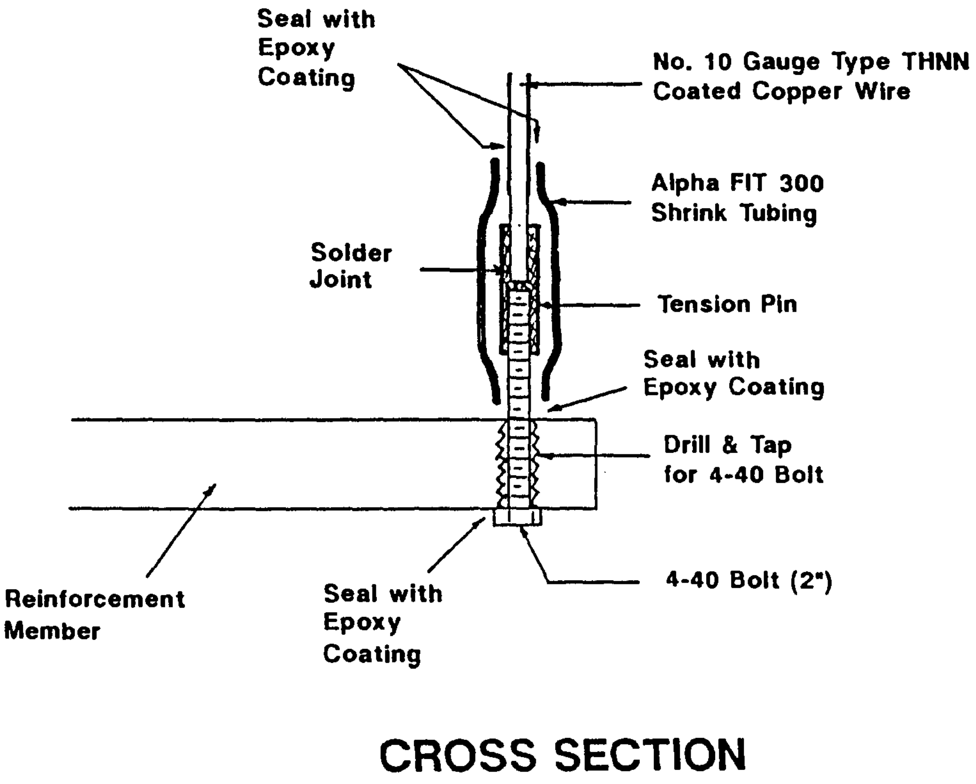


Figure 19. Schematic diagram for connection to reinforcing members

Stage 2 is established when the potential of the structure becomes more positive than the zinc coupon and approaches the potential of the steel coupon. During Stage 2, the following monitoring should be performed:

- Potential measurements on each coupon and structure to establish the change from one stage to another.

- PR measurements on steel coupons to provide a conservative (high) estimate of the corrosion rate of the structure. PR measurements on the structure would yield mean values as the actual exposed area is largely unknown, and therefore the conversion constant uncertain.

- Begin retrieval of the galvanized coupons to quantitatively evaluate the condition of the structure.

Stage 3 is established when the potential of the structure becomes similar to the potential of the steel coupon. At this stage, little or no galvanized coating remains. During Stage 3, the following monitoring should be performed.

- PR measurements on steel coupons and the structure to estimate the corrosion rate (metal loss) of the structure.

- Potential measurements on galvanized coupons for comparison to structure, until the potentials of the steel and galvanized coupons are similar to the structure.

- Continue to periodically retrieve the galvanized coupons to evaluate the condition of the structure.

Reinforcement must be isolated from the rest of the structure to permit monitoring of the actual reinforcement members. Instrumentation of the reinforcement strips should be performed in pairs, such that two parallel strips are instrumented. On new structures, "dummy" pairs of reinforcement members are instrumented and placed in the structure at the desired location such that no contact is made to the actual members of the structure or to the concrete panels. The instrumented members should be positioned such that 1 to 2 ft. (0.3 to 0.6 m) separation exists between the members of the pair.

The instrumented pairs will be exposed to the same conditions as the actual members except that the stress profiles along the instrumented members will be somewhat different since the instrumented members will not be connected to the concrete panels of the wall.

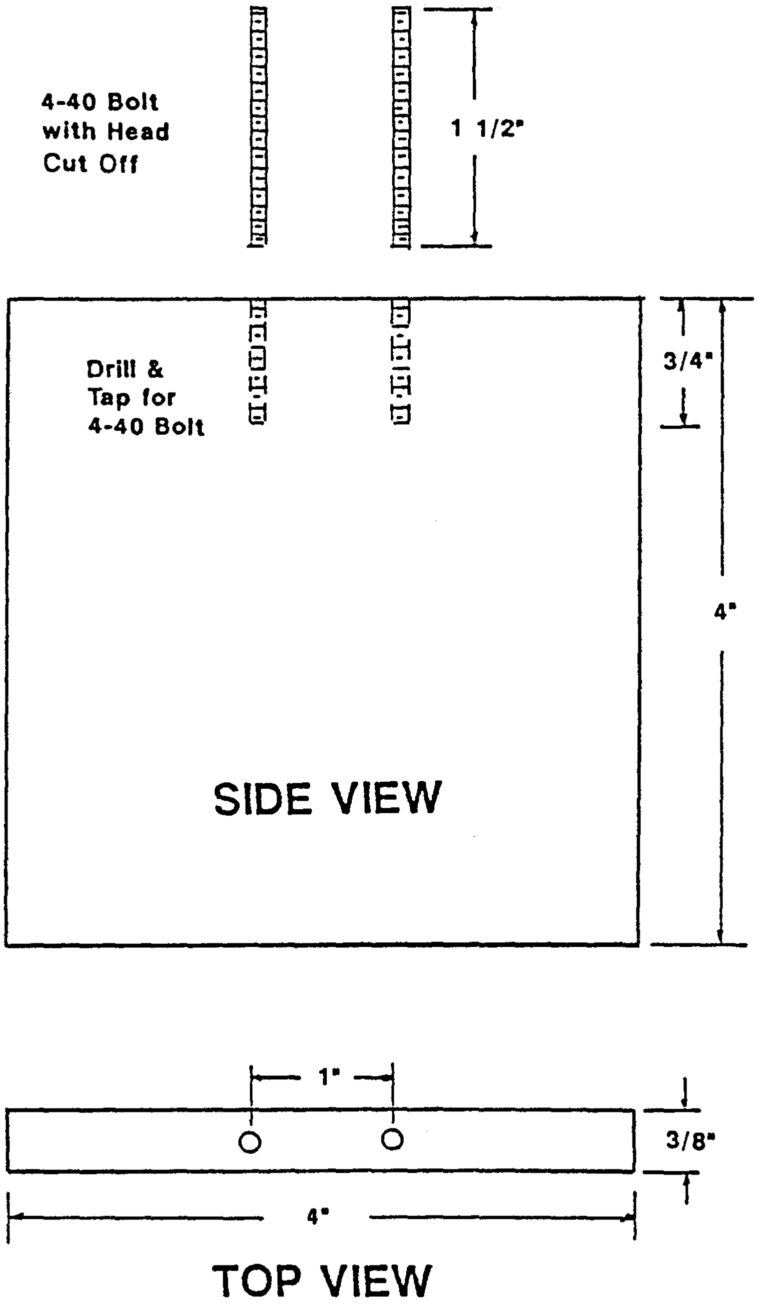
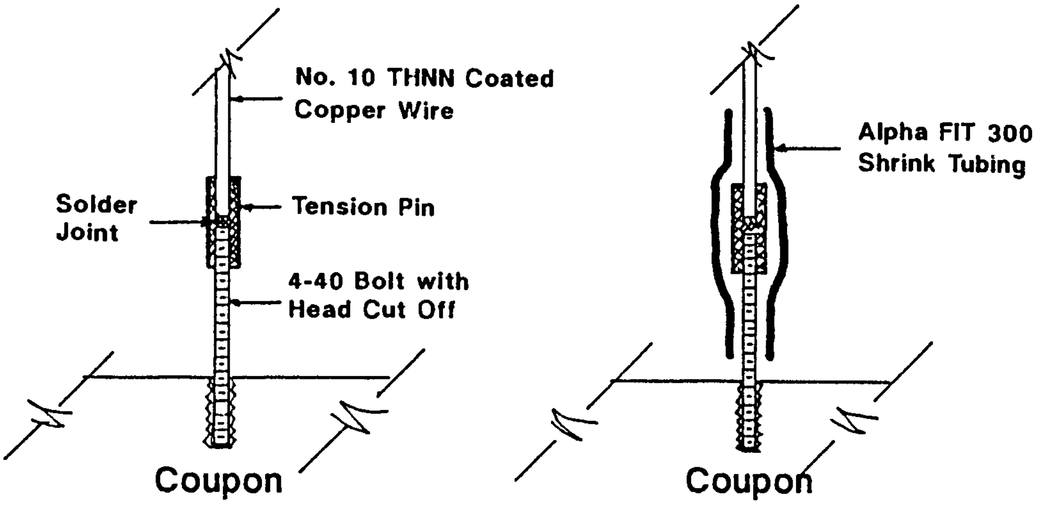
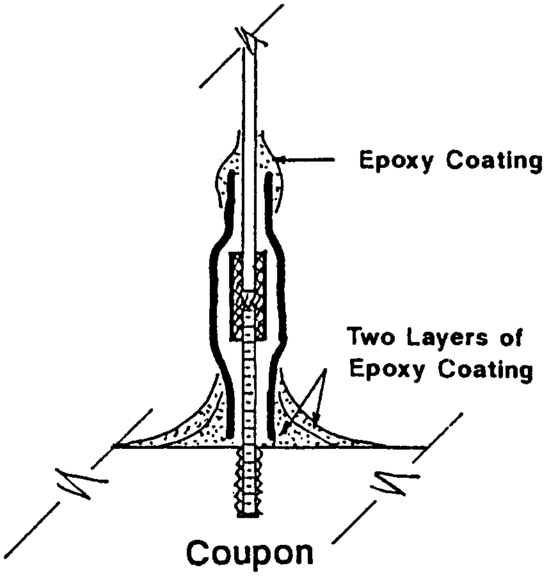


Figure 20. Schematic diagram for coupons



(a) Thread 4-40 Bolt Into Coupon and Cut Off Head. Solder No. 10 Wire, Using Tension Pin for Support.

(b) Shrink Tubing Down to Top of Coupon



(c) Apply Epoxy Coating

Figure 21. Schematic diagram illustrating coupon connection

The isolated strips will become test strips for making PR and potential measurements. The procedure for attaching test leads will be similar to that described for galvanizing coupons. The connection is shown schematically in figure 19. Two connections will be made on each instrumented strip, for redundancy.

For structures which have grid type reinforcing members, the procedures for instrumenting members will be similar to those previously described for reinforcement strips. If the connections to the front wall panels for grid systems are not tied to the rebar cage and the grid members are electrically isolated from each other, there is no need for "dummy" members to be placed in the wall.

(b) Old Structures

For old structures, excavation must be performed to reach the desired instrumentation level and isolation should be accomplished by removing a 1 to 2 ft. (0.3 to 0.6 m) section of the reinforcement strip at a point 5 to 10 ft. (1.5 to 3 m) from either end of the strip. This removed section will also permit the condition of the reinforcement strip to be determined. The remaining section at either end of the reinforcement strips should be periodically excavated and 1 ft.(0.3 m) sections cut and removed for evaluation. The 1 ft.(0.3 m) sections removed from old structures serve the same purpose as the retrievable galvanized coupons used for new structures.

Sections will be removed from the grid members in a similar manner as described for the reinforcement strips.

Lead connections on both new and old structures will be made in a similar manner as described for the reinforcement strips and shown on figure 19.

2. Materials

(a) Carbon Steel Coupons

Carbon steel coupons are used to estimate the rate of corrosion on the reinforcement members once the galvanized coating is lost (or partially lost) i.e. Stages 2 and 3. The carbon steel coupons will also provide the potential of steel for comparison to the potential of the reinforcement members in establishing when all galvanization has been lost (Stage 3). The carbon steel coupons should be made of similar materials as the reinforcement members. Exact duplication is not necessary since small concentration variations do not typically have a significant effect on general corrosion of carbon steel in soil.

The coupons are described as follows and are shown in figure 20 and 21:

- Coupon size is 4 in. by 4 in. by 3/8 in.(10 cm. by 10 cm. by 1 cm.)
- The top edge is drilled and tapped at two locations.
- Coupon surfaces are finished to a 600 grid finish (320 to 600 is acceptable).
- A 40-4 bolt is threaded into the top of the coupon and the head cut-off.
- A No. 10 gauge type THNN coated copper wire test lead (red) is soldered to the 4-40 bolt using a tension pin to provide support to the solder joint.
- The solder joint should be sealed with Alpha FIT 300 shrink tubing and the ends coated with Carboline coal tar epoxy coating including a 1-inch area of coupon around the connection (use two coats of epoxy, with each coat increasing in area covered).

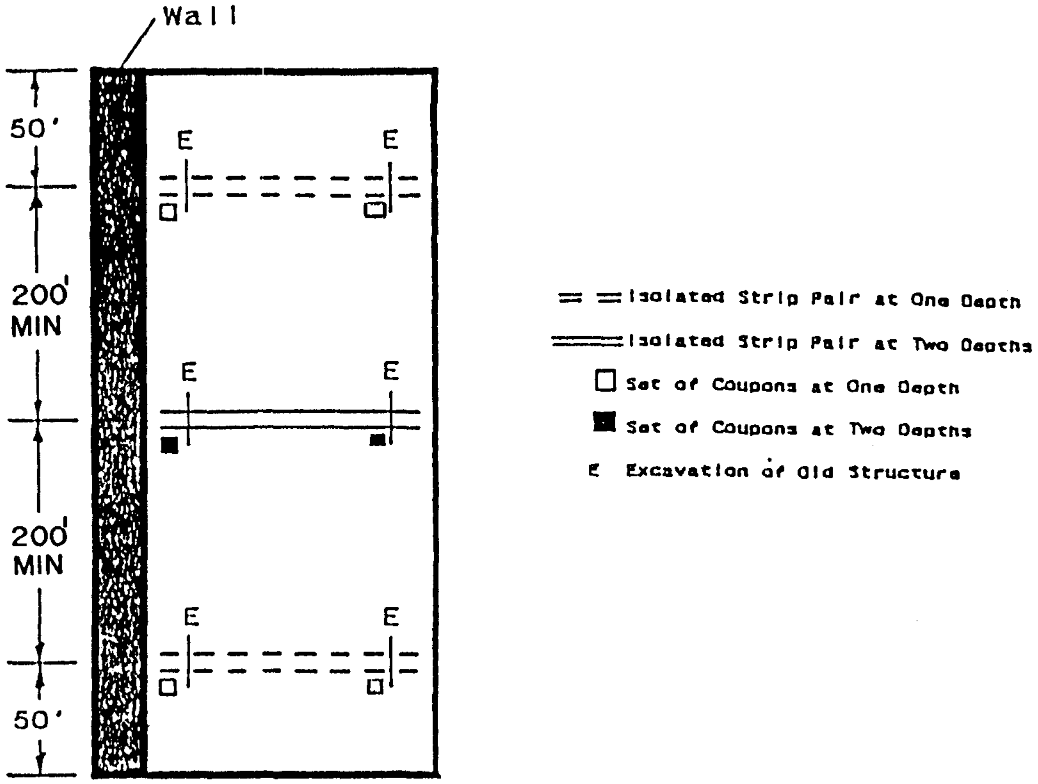
Masking off the lead wire from the environment is critical for obtaining the desired life of the coupon. Manufacturers cleaning procedures for epoxy application should be followed closely.

(b) Zinc Coupons

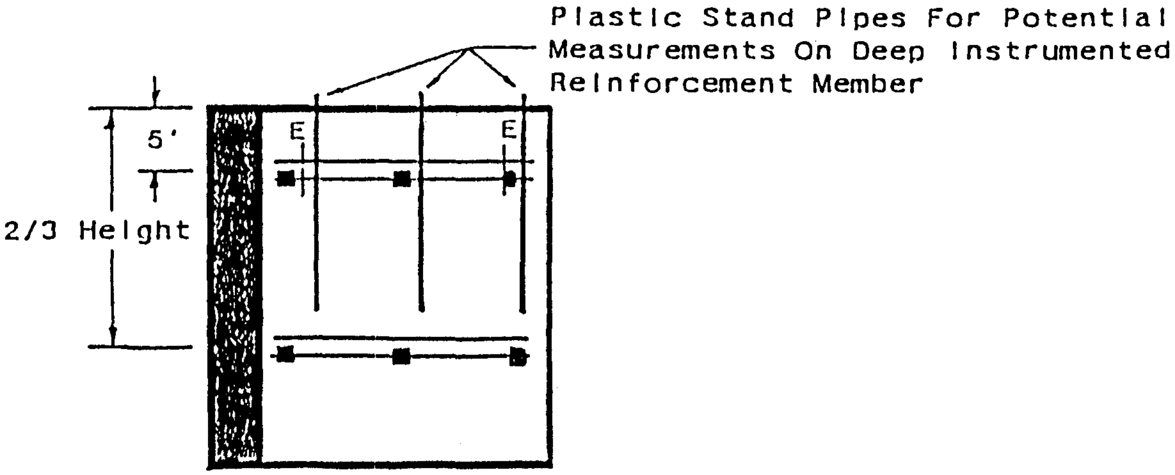
Zinc coupons are used to determine the rate of zinc loss which is an estimate of the rate of galvanization removal from structure (Stage 1). The zinc coupons should also provide the potential of zinc for comparison to the potential of the reinforcement members for establishing the transition from Stage 1 to Stage 2. The zinc coupons should be made of solid zinc and should have a typical composition of zinc used for galvanizing.

The configuration of the coupon should be similar to that of the carbon steel coupon, with the following exceptions:

- The shape of the coupon may be round instead of square depending on the availability of the zinc. Size should be 3 to 5 in.(7.6 to 12.7 cm.) in diameter.
- The test leads are black.
- The 4-40 bolt should be galvanized.



(a) Top View



(b) Side View

Figure 22. Schematic diagram showing locations of coupons and instrumented reinforcement members

(c) Galvanized Coupons

Galvanized coupons should be buried in new structures for periodic extraction to determine the condition of the galvanized coating and the steel substrate. The coupons should be made from reinforcement members. The cut edges of the coupons should be redipped in a zinc bath to provide a galvanized coating at the cut edges. Coupons should be both of the retrievable type and instrumented type. The retrievable type should be placed behind openings cut in the face panels and may be up to 4 ft. (1.2 m.) long.

The instrumented coupons should have the following configurations:

- Coupon size is 12 in.(0.3m) long (thickness or diameter will be the same as the strip reinforcement member).
- A single 4-40, 2 in. (5 cm) bolt should be threaded through a drilled and capped hole in the end of the coupon prior to regalvanizing the edges so that the rod also can be galvanized.
- The No. 10 Gauge Type THNN coated copper wire test lead (white) is soldered to the bolt using a tension pin to provide support for the solder joint.
- The connection and down to the top of the coupon is sealed with Alpha FIT 300 shrink tubing, and the ends and the solder connection is coated with the carboline epoxy coating (use two coats of epoxy with each coat increasing in area covered).

3. Monitoring Schemes

It is desirable to have both coupons and instrumented reinforcement members at two depths as a minimum, because differences in oxygen content, moisture content, and salt concentration can produce different corrosion behavior. Higher oxygen and salt content are anticipated near the surface, while higher moisture contents or free water, near the base of each structure.

The short term limited field program has indicated that where groundwater intrudes at the base of the structure, higher corrosion rates should be anticipated. Where this condition is not likely, estimates may be obtained from shallow depth monitoring.

Ideally, three types of coupons should be placed at each test station: zinc, steel and galvanized (new structures only). At old structures, galvanized coupons will not be used and sections of the actual structures will be periodically removed instead.

For long term monitoring of structures, it is desirable to have 1-zinc, 1-steel and up to 4-galvanized coupons at each location. The multiple galvanized coupons are for periodic removal. Coupons each have 2 leads to provide back-up in case one connection fails.

The test station should be a water-tight box with the ability to lock. The front panel should have the capacity to provide isolated test lead connections. The total number of connections will depend on the number of coupons buried. All leads should be encased in conduit to prevent breakage of the leads.

The reinforcement members should be isolated in pairs to provide parallel test specimens. Each instrumented member should have two sets of leads to provide a back-up lead in case one connector fails. The leads should be encased in conduit down to the reinforcement member to help prevent breakage of the test leads. The same test station used for the coupons can be used for the instrumented reinforcement members if it is convenient.

Figure 22 shows the location of the coupons and instrumented reinforcement members. For long-term monitoring, 3 test positions (top view) are desirable for structures over 500 ft. (155 m.) For structures under this length 2 test positions will suffice. One critical position (center of structure) should be selected for establishing test locations at both a shallow and deep position. For structures over 500 ft. (155 m.) in length, two or more positions should be considered for monitoring at two depths. The shallow depth stations should be approximately 5 ft. (1.5 m.) in depth and the deep position should be approximately at 1/3 of the structure height from base level.

Similar location selection criteria apply for old and new structures. However, it is realized that for old structures, only the shallow depth may be practical. This location may not yield the maximum corrosion rates.

Potential measurements must be made at the time of installation to check lead connections and establish initial measurement values. Subsequent measurements are recommended monthly for the first 3 months, bi-monthly for the next 9 months, to determine seasonal variations, if any, and annually thereafter at approximately the same yearly time.

Potential measurements should be made for each coupon and for each instrumented reinforcement member at each end of the member and at 8 ft. (2.4 m.) intervals along the reinforcement member when elements are greater than 25 ft. (7.6 m.) in length.

Polarization resistance measurements should be made at the same frequency and schedule. For long term monitoring schemes, four galvanized coupons should be buried and the first coupon should be removed at the midrange of Stage 2, the second at the beginning of Stage 3, and the remaining two at intervals established by the predicted metal loss from PR measurements.

For old structures, the isolation of the reinforcement member should be accomplished by removing a 1 to 2 ft. (0.6 m.) section at a point 5 to 10 ft. (1.5 to 3 m.) from either end of the reinforcement member. The sections removed during initial excavation are used for evaluations to establish the starting condition for monitoring. The remaining sections at either end can serve the same purpose as the galvanized coupons used for new structures and the middle section can be instrumented. For long term monitoring schemes, excavations can be performed and a 1 ft. (0.3 m.) section removed from the remaining sections at either end of the reinforcement members. These excavations should be performed at the midrange of Stage 2, at the beginning of Stage 3, and at intervals established by the predicted metal loss from PR measurements thereafter.

4. Measurement Procedures

(a) Potential measurements

Potential measurements are relatively simple measurements that can be performed with a minimum of equipment, application time and experience. Recommended equipment is a high impedance voltmeter (100 Mohm or greater).

Prior to field measurements, the equipment should be checked as follows:

- Calibrate voltmeter if it has not been done recently (see instruction manual).

- Zero voltmeter.

- Measured differences between all reference electrodes, should be less than 5 mV. If not, check solution level and be sure Cu_2SO_4 crystals are present. The crystals should be loose, not packed together. If potential differences persist, add fresh Cu_2SO_4 crystals and distilled water (always be sure some crystals remain in solution). Clean copper rod with 600 grit silicon carbon paper and reassemble electrode. Check potential differences again.

The field procedure to obtain measurements is as follows:

(1) Place reference electrode near the test station, insuring that good earth contact is made. (For dry areas, water can be poured on the ground to decrease contact resistance between electrode and earth).

(2) Connect positive lead (red) of voltmeter to reference electrode.

(3) Connect negative lead (black) of voltmeter to designated potential measurement test lead at test station.

(4) Read potential on voltmeter.

(5) Potential value of specimen being measured will have an opposite sign than read on voltmeter, e.g. if the voltage of a galvanized specimen is +1.042 V, then the potential of specimen with respect to the reference electrode is-1.042 V Cu_2SO_4 .

(6) Read voltages to nearest mV.

The instrumented reinforcing members are used for corrosion potential surveys with distance relative to a reference electrode placed at and moved along the top surface of the structure. The corrosion potential survey will assess whether there is possible macrocell corrosion activity created by differences in near wall versus far wall conditions. The polarization resistance measurements will determine the average corrosion rate of the entire reinforcement.

(b) Polarization Measurements

Polarization resistance measurements require the application of a potential and resulting current to the specimen being examined, with simultaneous measurement of the potential and current. The acquired data is processed to calculate the polarization resistance and to estimate the corrosion rate of the specimens. Standard methods for performing polarization resistance are outlined in ASTM G-59-78 (reapproved 1984). Soil resistance measurement equipment is typically needed for correcting polarization resistance measurements for R_{ohm}.

Fully automatic equipment for making polarization resistance measurements, soil resistance measurements and integrating all data have been developed under this program and are now commercially available.

From the corrected polarization (for soil resistance) the corrosion current can be calculated from:

$$i_{cor}(A/cm^2) = \frac{0.05}{R_p} \quad \text{(zinc surface)} \qquad (10)$$

$$i_{cor}(A/cm^2) = \frac{0.035}{R_p} \quad \text{(steel surface)} \qquad (11)$$

and corrosion rates in um per year by:

$$CR\ (um/yr) = \frac{i_{cor}(A/cm^2)}{8.6x10^{-8}} \quad \text{(for steel)} \qquad (12)$$

$$CR\ (um/yr) = \frac{i_{cor}(A/cm^2)}{6.7x10^{-8}} \quad \text{(for zinc)} \qquad (13)$$

The polarization resistance measurements on the reinforcement can be made in one of two ways. First, a conventional three electrode approach can be taken utilizing a Cu/Cu_2SO_4 reference electrode at the surface and utilizing the adjacent strip in the pair as the counter electrode. The alternative is to measure the polarization resistance between the two adjacent strips without a reference electrode. This is in principle valid for conventional polarization resistance measurements since what is measured is the sum of the total polarization resistance of each of the two strips.

If this latter approach is followed, care should be taken to assure that the results so obtained compare well with those via the conventional three electrode method.

Complete field procedures using the developed automatic equipment are presented in appendix B.

CHAPTER 5 SYSTEM EVALUATION

1. General

The developed concepts, methods and equipment to determine corrosion rate on both new and existing structures have been evaluated at 5 existing structures and 2 new structures. Details, analyses and results are summarized in this chapter.

2. New Structures

The Algonquin test sites for FHWA RD-89-043 consist of adjoining structures constructed with galvanized steel strips and grid reinforcement mats connected to a precast concrete facing. Each structure is 35 ft. (10.6 m.) long and 20 ft. (6 m.) high. Backfill consists of a sandy gravel with measured resistivity as high as 80,000 ohm/cm at placement moisture content and 15,000 ohm /cm at saturation. The two sites are identified as follows:

. Site 4 - Galvanized Strip Site.

. Site 5 - Galvanized Grid Site.

At each site, coupons and instrumented reinforcement members were initially buried at a lower elevation (level 3) and as the construction progressed, a second set of coupons were buried at a higher elevation (level 6) in the same vertical section. The instrumented reinforcement member consists of a full length strip, or grid member isolated from the wall. Duplicate test leads from each coupon and instrumented reinforcement member were brought to the surface and connected in a test box. At each site, the initial free-corrosion potential and polarization resistance (PR) was measured for each coupon and instrumented reinforcement member. As for all sites, the soil resistance in the PR measurements were compensated for.

Site 4 - Is a new construction Reinforced Earth^{TM} test wall using galvanized strip. The instrumented reinforcement strips are full size members 14 ft. (4.3 m.) long. The two instrumented members were labeled Structures 1 and 2, with Structure 1 being the right hand strip facing the outside of the wall. In between the two strips, steel, zinc and galvanized coupons were buried.

A summary of results for this site is shown on tables 8 and 9 and with typical data obtained during one site visit reported in appendix A.

Table 8. Summary of field results, site 4, lower level

Test Specimens	Exposure Times Initial Data	 2 Months	 8 Months	 15 Months	 26 Months
E_{cor}[a], Steel	-0.548	-0.458	-0.400	-0.329	-0.351
Corrosion Rate[b], Steel	6.5	3.2	1.9	10	11
E_{cor}, Zn	-0.915	-1.000	-0.921	-0.830	-0.963
Corrosion Rate, Zn	55	2.5	0.4	1.2	1.1
E_{cor}, Galvanized	-0.938	-0.708	-0.775	-0.781	-1.014
Corrosion Rate, Galvanized	43	1.0	0.4	1.6	2.7
E_{cor}, Structure 1	-0.976	-0.681	-0.870	-0.654	-0.710
Corrosion Rate, Structure 1	7.6	1.2[c]	0.9	1.8	0.9
E_{cor}, Structure 2	-1.005	-0.793	-0.920	-0.663	-0.756
Corrosion Rate, Structure 2	4.5	0.8[c]	0.6	1.3	0.6

[a] Free-corrosion potential, V($Cu/CuSO_4$).

[b] Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr unless otherwise noted.

[c] Corrosion rate estimated from polarization resistance not corrected for soil resistance. The corrected value would be a higher corrosion rate.

Table 9. Summary of field results, site 4, upper level

	Exposure Times			
Test Specimens	Initial Data	6 Months	13 Months	24 Months
E_{cor}[a], Steel	-0.500	-0.310	-0.221	-0.293
Corrosion Rate[b], Steel	1.5	0.4	4.7	9.9
E_{cor}, Zn	-1.055	-0.950	-0.770	-0.884
Corrosion Rate, Zn	1.5[c]	0.5	0.7	0.8
E_{cor}, Galvanized	-1.040	-0.835	-0.554	-0.669
Corrosion Rate, Galvanized	1.6[c]	0.5	0.7	0.7
E_{cor}, Structure 1	-1.012	-0.915	-0.603	-0.757
Corrosion Rate, Structure 1	0.6[c]	1.6	1.7	0.8
E_{cor}, Structure 2	-0.980	-0.925	-0.594	-0.653
Corrosion Rate, Structure 2	0.6[c]	1.2	1.3	0.8

[a] Free-corrosion potential V(Cu/$CuSO_4$).

[b] Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

[c] Corrosion rate estimated from polarization resistance not corrected for soil resistance. The corrected value would be higher.

The significant fluctuations of potentials to some extent are believed to be influenced by seasonal moisture and temperature changes. Soil resistance accounts for a significant portion of the polarization resistance measured, which was not anticipated in light of the high resistivity backfill used. Therefore, correcting for soil resistance is critical in determining accurate corrosion rates. Corrosion rates for the galvanized members after 2 year burial are less than 1 um/year and for bare steel about 10 um/year which is generally consistent with index properties of 15,000 ohm/cm. Interpretation of potentials without coupon data for reference would be extremely difficult.

Site 5 - Is a new construction Retained Earth^{TM} test wall using galvanized grid. The instrumented reinforcement grids (Structures 1 and 2) are full-size members (15 ft. (4.6 m.) long. In between the two grid members, steel, zinc and galvanized coupons were buried. Potential and corrosion rate data exhibits the same trends and is nearly identical as for strips confirming the validity of the method for both typical reinforcement configurations. Summary results for this site is shown on tables 10 and 11 with typical data obtained during one site visit reported in appendix A.

Tafel slope measurements at this site have been made on selected zinc, steel and galvanized coupons yielding constants varying between 0.042 and 0.057 which are consistent with the range of 0.035 to 0.050 previously developed and used for interpretation of corrosion rates.

3. Existing Structures

(a) Site 1 is located along the connecting wall between two abutments carrying I-990 over Sweet Home Road in Buffalo, New York. The Reinforced Earth^{TM} wall was approximately 5 years old at time of instrumentation. The backfill utilized was a lightweight gravelly sand of manufactured origin. The resistivity at saturation was measured at 1,600 ohm/cm, while the resistivity in the actual structure is somewhere between 7,000 (20 percent moisture) and 16,000 ohm/cm (10 percent moisture). Coupons and Structure 1 and 2 test specimens (strips) were instrumented in the top layer of strips on the north bank of Sweet Home Road. The original strips were 14 ft. (4.3 m.) in length. Adjacent strips were sectioned and one-foot specimens were removed such that the remaining instrumented strips were 5 ft., 7 in. (1.7 m.) and 6 ft., 6 in. (2 m.) length and labeled Structure 1 and 2, respectively.

After significant stabilization time (9 months) the relative differences in potentials were as anticipated. The significant

Table 10. Summary of field results, site 5, lower level

		Exposure Times			
Test Specimens	Initial Data	2 Months	8 Months	15 Months	26 Months
E_{cor} (a), Steel	-0.536	-0.360	-0.318	-0.279	-0.299
Corrosion Rate (b), Steel	11	17	2.8	7.8	8.2
E_{cor}, Zn	-1.031	-1.220	-0.835	-0.890	-0.967
Corrosion Rate Zn	11	2.7	0.5	1.0	0.8
E_{cor}, Galvanized	-1.016	-0.990	-0.680	-0.632	-0.673
Corrosion Rate, Galvanized	20	6.8	0.7	1.3	0.9
E_{cor}, Structure 1	-1.069	-0.866	-0.950	-0.777	-0.817
Corrosion Rate, Structure 1	4.4	2.0	0.6	1.3	0.7
E_{cor}, Structure 2	-1.067	-0.845	-0.935	-0.736	-0.800
Corrosion Rate, Structure 2	4.6	2.5	0.6	1.3	0.7

(a) Free-corrosion potential, V(Cu/$CuSO_4$).

(b) Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

Table 11. Summary of field results, site 5, upper level

	Exposure Times			
Test Specimens	Initial Data	6 Months	13 Months	24 Months
E_{cor}[a], Steel	-0.526	-0.337	-0.295	-0.307
Corrosion Rate[b], Steel	22	1.8	8.9	12.3
E_{cor}, Zn	-0.970	-0.994	-0.773	-0.927
Corrosion Rate, Zn	1.6[c]	0.7	0.9	1.3
E_{cor}, Galvanized	-1.015	-0.839	-0.588	-0.688
Corrosion Rate, Galvanized	3.5[c]	1.1	1.4	1.3
E_{cor}, Structure 1	-0.984	-1.008	-0.686	-0.806
Corrosion Rate, Structure 1	2.1	1.8	1.4	1.1
E_{cor}, Structure 2	-0.970	-0.996	-0.677	-0.826
Corrosion Rate, Structure 2	4.9	2.0	0.2	0.9

(a) Free-corrosion potential V(Cu/$CuSO_4$).

(b) Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

(c) Corrosion rate estimated from polarization resistance not corrected for soil resistance. The corrected value would be higher.

Table 12. Summary of field results, site 1

Test Specimens	Exposure Times			
	24 Hours	3 Months	9 Months	14 Months
E_{cor}(a), Steel	−0.448	−0.379	−0.347	−0.324
Corrosion Rate(b), Steel	0.6	9.9	3.7	2.6
E_{cor}, Zn	−0.569	−0.467	−0.624	−0.664
Corrosion Rate, Zn	1.3	2.8	6.3	11
E_{cor}, Galvanized	−0.568	−0.442	−0.529	−0.603
Corrosion Rate, Galvanized	0.8	3.9	8.2	17
E_{cor}, Structure 1	−0.450	−0.510	−0.495	−0.607
Corrosion Rate, Structure 1	0.7	3.2	6.4	6.1
E_{cor}, Structure 2	−0.441	−0.487	−0.482	−0.530
Corrosion Rate, Structure 2	0.6	2.0	3.8	1.4

(a) Free-corrosion potential, V(Cu/$CuSO_4$).

(b) Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

Table 13. Summary of field results, site 2

Test Specimens	Exposure Times			
	24 Hours	3 Months	9 Months	14 Months
E_{cor}[a], Steel	+0.487	+0.380	−0.232	−0.282
Corrosion Rate[b], Steel	570	150	37	29
E_{cor}, Zn	+0.469	+0.426	+0.460	+0.407
Corrosion Rate, Zn	1,300	3,400	2,400	880
E_{cor}, Galvanized	+0.483	+0.442	+0.470	−0.106
Corrosion Rate, Galvanized	1,500	>4,400	3,100	89
E_{cor}, Structure 1	+0.405	+0.340	+0.352	+0.160
Corrosion Rate, Structure 1	79	130	64	150
E_{cor}, Structure 2	+0.405	+0.387	+0.437	+0.339
Corrosion Rate, Structure 2	69	450	140	260
E_{cor}, Structure 3	−0.246	−0.302	*	*
Corrosion Rate, Structure 3	37	120	*	*

(a) Free-corrosion potential, V($Cu/CuSO_4$).

(b) Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

* Structure 3 is no longer available for testing.

zinc consumption rate calculated on the coupons (>10 um/y) is consistent with relatively high corrosion rates in the first years in low resistivity soils, while the somewhat smaller average rates on the strips (3.5 um/y) are consistent with continuing rates (4 um after 2 years). Weight loss analyses from a retrieved sample indicated that 89 um of galvanization remained which is in excess of the specified minimum of 86 um. However, actual initial thickness of galvanization is not known and is often in excess of 100 um.

At this site, the soil resistance correction was significant as anticipated. A summary of results for this site is shown on table 12 with typical data obtained during a site visit reported in appendix A.

(b) <u>Site 2</u> is located behind the connecting wall between the abutments carrying I-990 exit ramps over Sweet Home Road and Bizer Creek in Buffalo, New York. The Reinforced Earth^{TM} wall was 6 years old at time of instrumentation. The backfill utilized was a cinder fill. The cinders have a resistivity at saturation of 40 ohm/cm, while the resistivity in the actual structure is somewhere between 60 and 100 ohm/cm. The pH of the cinders in contact with the steel strips was between 2.5 and 3. A slurry of cinders and distilled water taken from the bulk structure produced a 3.7 pH. Previous resistivity measurements of samples taken during construction indicated a range of 65 to 300 ohm/cm. Chloride content was determined to be zero and sulfates varying between 2100 and 2700 P.P.M.

The coupons and Structures 1, 2 and 3 test specimens were instrumented in the top layer of strips on the west embankment. The original strips were 17 ft. (5.2 m.) in length. The 1 ft. (0.3 m.) specimens were removed such that the remaining strips were 6 ft. (1.8 m.) in length for Structures 1, 2 and 3. The steel, zinc, and galvanized coupons were placed between the Structure 1 and 2 specimens. The free-corrosion potential of the steel, zinc and galvanized coupons all indicated extreme corrosion activity as these values are very positive for underground structures. The potential data throughout is indicative of extreme corrosion activity, which is reinforced by corrosion rate measurements, and examination of samples.

A summary of field results for this site is shown on table 13, with typical data obtained during a site visit reported in appendix A.

Sample specimens removed from Structure 1, 2 and 3 strips had undergone severe corrosion, with the samples from Structures 1 and 2 much worse than Structure 3. This corresponds to the measured free-corrosion potentials since the potentials of Structures 1 and 2 were more positive than Structure 3.

The average corrosion rate based on dimensional analyses of samples from strips and polarization resistance measurements are shown on table 14, in addition to average loss data obtained from the last 8 feet of the adjacent strips recovered during the reconstruction phase.

Table 14. Corrosion losses site 2

Location	Corrosion Losses um/year		
	Adjacent Strips full length strips	Wt. Loss Analysis sample	PR Measurements half length strips
Structure 1	180	242	107 (9-14 mo.)
Structure 2	180	167	200 (9-14 mo.)
Structure 3	180	65	120 (3 mo.)

It must be understood that corrosion rates obtained from PR measurements yield average corrosion rates for the whole reinforcing length being measured. The weight loss samples represent only a portion 9 to 12 in. (0.23 to 0.3 m.) of the strip.

Coupons placed during the initial construction in the adjoining end slope in the same backfill and excavated exhibited significantly smaller corrosion rates losing an average 2 percent section per year as compared to 8 percent per year for strips in the actual structure.

This comparative data would suggest that corrosion rates obtained solely from coupons may not be fully indicative of the magnitude of corrosion occurring since it is difficult to pre-determine areas of maximum corrosion. The coupons were valuable in suggesting higher than normal corrosion activity, but significantly underestimated the severity of the problem.

The severe corrosion found at this structure prompted NYDOT to replace the Reinforced Earth^{TM} wall. Prior to replacement, an extensive survey was made which recovered reinforcing strips at

Table 15. Summary of field results, site 3

Test Specimens	Exposure Times			
	24 Hours	3 Months	9 Months	14 Months
E_{cor}(a), Steel	-0.588	-0.561	-0.644	-0.672
Corrosion Rate(b), Steel	29	37	69	72
E_{cor}, Zn	-1.035	-1.119	-1.085	-1.125
Corrosion Rate, Zn	17	23	6.1	11
E_{cor}, Galvanized	-1.036	-1.072	-1.050	-1.079
Corrosion Rate, Galvanized	7.5	4.0	1.5	5.0
E_{cor}, Structure 1	-1.041	-1.077	-1.024	-1.072
Corrosion Rate, Structure 1	7.1	7.8	3.6	5.9
E_{cor}, Structure 2	-1.032	-1.032	-1.047	-1.073
Corrosion Rate, Structure 2	9.5	6.6	8.3	12

(a) Free-corrosion potential, V(Cu/$CuSO_4$).

(b) Corrosion rate estimated from polarization resistance corrected for soil resistance, um/yr.

every depth along a vertical section. The measured thickness along the length of each strip varied considerably, even though no pitting was observed. Greater corrosion loss was found near the back of the structure and at the greater depths in all cases.

Typical variations with length for one strip are shown on figure 7. Mean thickness as a function of distance from the face and depth from the surface for all strips recovered is shown on figure 23.

(c) <u>Site 3</u> is located on the abutment slope of Rt. 263 over Maple Avenue in Buffalo, New York. This 2-year old Retained Earth^{TM} structure was constructed with galvanized grid reinforcements and backfilled with a crushed sandy gravel. The backfill has a resistivity of 700 to 2800 ohm/cm and chloride and sulfate concentrations of 400 to 500 PPM.

Coupons were buried and Structures 1 and 2 test specimens instrumented on the top row of the wing wall area. No samples were removed from the instrumented grid members. The instrumented length of the Structures 1 and 2 are 10 ft. and 13 ft. (3 and 4 m.) respectively.

The free corrosion potentials of the steel coupon is much more positive than for zinc and galvanized coupons. The potentials of Structures 1 and 2 are similar to the zinc and galvanized coupons which indicates that the structure is well galvanized. This was confirmed by visual inspection of the grid members during instrumentation. The corrosion rates measured on the galvanized grid average 8 um/year which is consistent with the design rate for the first few years and not unanticipated in light of the relatively low resistivity and high chloride/sulfate concentrations. Unless subsequent data shows a dramatic decrease of corrosion, the galvanization would be substantially depleted in 15 years.

The steel coupon reflects the relatively high anticipated rate of corrosion for carbon steel in the first years, consistent with low resistivity and high chloride, sulfate content.

A summary of results for this site is shown on table 15 with typical data obtained from a site visit reported in appendix A.

(d) <u>Site 4</u> is located 4 miles north of the City of Cloverdale, California on a new alignment of State Route 101. This 2-year old Retained Earth^{TM} Structure of maximum height of 62 ft. 19 m.) was constructed with galvanized grid reinforcements and backfilled with a generally cohesionless fill with physical properties as shown on table 16.

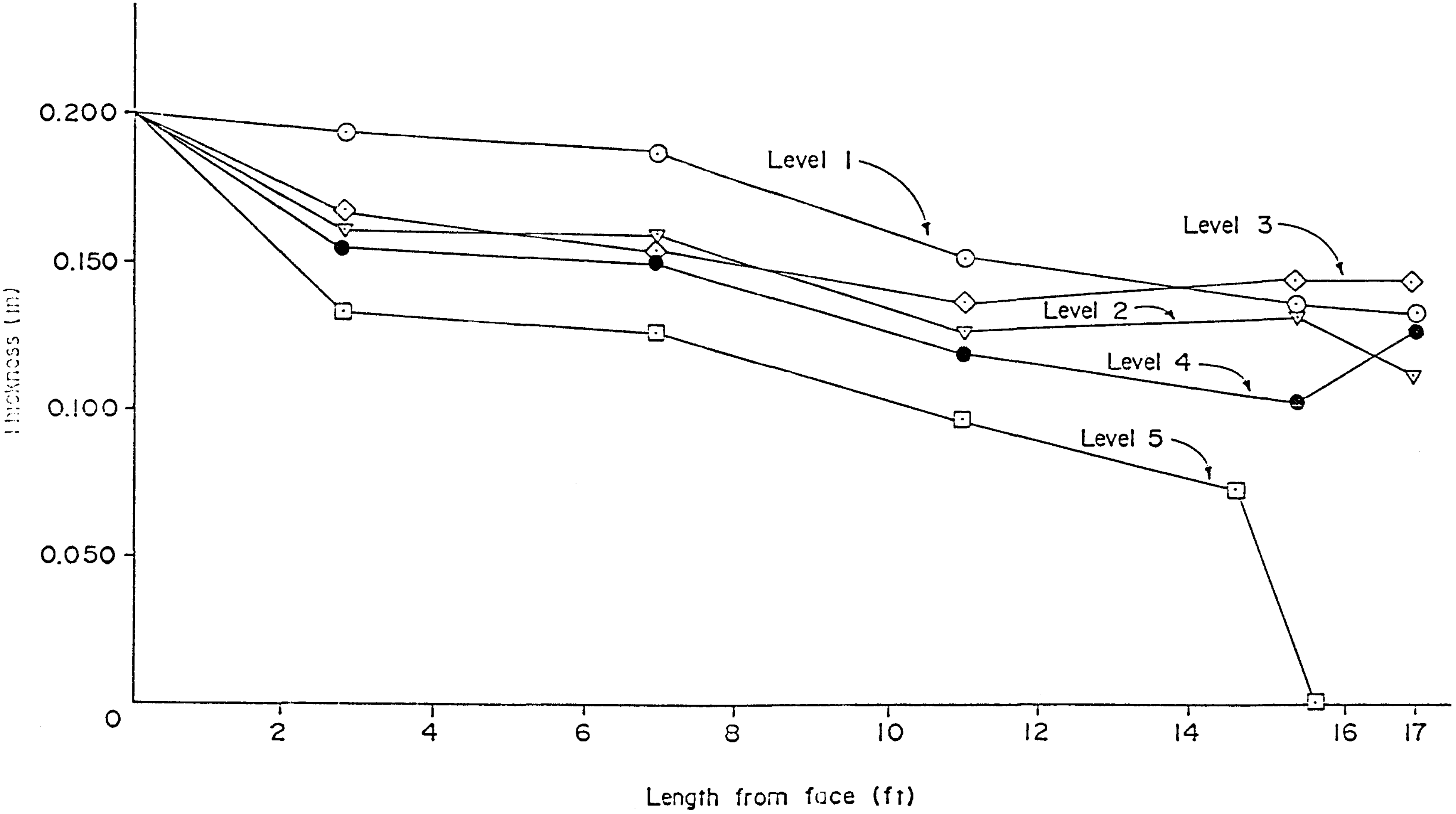


Figure 23. Average thickness loss vs. depth from surface

Table 16. Physical properties, site 6

Mechanical Properties		Electrochemical Properties	
-6"	- 100%	Resistivity	2800 to 7500 ohm/cm
+#4	- 65%	pH	5.1 - 7.7
-#200	- 10%	Chlorides	<40 PPM
P.I.	-10 to 12	Sulfates	<69 PPM
L.L.	-30 to 32		

The site was fully instrumented by Caltrans personnel during construction, and provisions made for sample removal at future dates.

The instrumentation consists of groups of coupons and instrumented reinforcement members located at heights of 20 ft. (6 m.), 40 (12 m.) and 50 ft. (15.2 m.) above the base of the wall. For each depth, steel and galvanized coupons are located at 6 ft. (2 m.) and 34 ft. (10.3 m.) from the face of the wall. At each location, four of the grid reinforcement members are instrumented with two wire leads coming to the test box. Buried in the structure are reference zinc, copper and silicon iron electrodes. The zinc electrodes are bagged bentonite and gypsum (standard anode backfill) and therefore, do not necessarily represent the free-corrosion potential of zinc or the corrosion rate of zinc in the natural environment. The copper coupons provide a reference potential, but have little direct meaning to the evaluation of the corrosion behavior of the reinforcement members. The silicon iron anodes were designed to provide current distribution to the coupons or reinforcement members during polarization type measurements. However, because of possible stray current interactions on the reinforcement members, these anodes were not used.

Full details of the complete instrumentation layout, connection details and construction methods are outlined in Caltrans Final Report 65321-641143.

The potential data obtained during the field visits as well as that previously obtained by Caltrans are consistent. They indicate that the free corrosion potentials of the grid reinforcement members and the galvanized coupons are more negative near the base of the wall and tend to become more positive at the shallower burial depth. It is difficult to determine the cause of this trend, but it is likely that for the shallower depths of burial, grid members and coupons are more subject to effects of moisture fluctuations or possibly oxygen.

In fact, a review of the Caltrans data indicates that the shallow burial depth undergoes much larger potential fluctuations as a function of time than the greater depths. In examining the galvanized coupon potentials at the different distances from the face of the wall, there is no clear trend in the free-corrosion potential at this early stage in the life of the structure.

In examining the free-corrosion potential of the carbon steel coupons, no trend is observed as a function of height above the base of the wall. However, in each case, the steel coupons buried at 34 ft. (10.3 m.) from the face of the wall have a more negative free-corrosion potential than those steel coupons buried 6 ft. (2 m.) from the face of the wall and exhibit somewhat lower corrosion rates. The steel coupons are always more positive than the galvanized coupons for each location, although the difference is slight at some locations. Because the free-corrosion potential of the galvanized coupons is similar to that of the grid members and because the free corrosion potential of the galvanized coupons is more negative than that of the carbon steel coupons, the grid members can be assumed to have significant galvanization.

Polarization measurements on grid reinforcements and coupons were made and corrected for soil resistance. The correction is minor for galvanized coupons and grid reinforcements, but significant for bare steel. This is primarily due to the higher corrosion rates for the steel coupons which in turn magnifies the solution resistance value since the error shows up as an IR (current times solution resistance) voltage error in the polarization resistance measurement.

The corrosion rates for the galvanized coupons correspond reasonably well to the corrosion rates obtained for the grid reinforcements members at each height. Corrosion rates for galvanized coupons at the back of the structure are somewhat higher, which is the opposite performance of steel coupons. The corrosion rates for the grid reinforcement members average less than 2um/year, with slightly higher rates at the bottom of the structure. These rates are within the low end of projected rates after the first 2 years.

The corrosion rates for the carbon steel coupons are approximately one order of magnitude higher than the corrosion rates measured for the galvanized coupons or grid reinforcement members. The lowest corrosion rates for the steel coupons correspond to those buried at the greatest depth. For the most shallow depth, both steel coupons at 6 and 34 ft.(2 and 10.3 m.) from the face of the wall have relatively high corrosion rates (30 and 40um/y, respectively), which are consistent with the projected rates in the first 2 years.

Table 17. Summary of field results, site 6, February 1989

No.	Description	Height Base	Distance From Wall	Area, cm^2	Free-Corrosion Potential, V, $Cu/CuSO_4$	Polarization Resistance, PR, ohm	PR, ohm * cm^2	CR, um/yr	Soil Resistance R_s, ohm	Corrected PR[(b)] ohm * cm^2	Corrected CR um/yr
BC-T-L	Grid	20'	-	34,290	-0.859	9.1	312,000	2.4	1.9	247,000	3.0
BC-T-R	Grid	20'	-	34,290	-0.856	9.2	315,000	2.4	3.4	199,000	3.8
BC-B-L	Grid	20'	-	34,290	-0.771	19.6	672,000	1.1	3.2	562,000	1.3
BC-B-R	Grid	20'	-	34,290	-0.789	17.2	590,000	1.3	3.4	473,000	1.6
Fe-BC-1-L	Steel(a)	20'	6'	478	-0.451	139	66,440	6.1	98	19,600	21
Fe-BC-2-L	Steel(a)	20'	34'	475	-0.598	133	63,175	6.4	44	42,275	9.6
Zn/Fe-BC-1-R	Galv(a)	20'	6'	482	-0.851	1970	949,500	0.8	135	884,400	0.8
Zn/Fe-BC-2-R	Galv(a)	20'	34'	485	-0.894	350	169,750	4.4	42	149,380	5.0
DE-T-L	Grid	40'	-	26,690	-0.735	15.5	414,000	1.8	2.5	347,000	2.2
DE-T-R	Grid	40'	-	26,690	-0.716	21.4	571,000	1.3	2.8	496,000	1.5
DE-B-L	Grid	40'	-	26,690	-0.763	18.4	491,000	1.5	2.8	416,000	1.8
DE-B-R	Grid	40'	-	26,690	-0.749	22.6	603,000	1.2	2.8	528,000	1.4
Fe-DE-1-L	Steel(a)	40'	6'	481	-0.464	86.0	41,400	9.8	60	12,500	32
Fe-DE-2-L	Steel(a)	40'	34'	475	-0.607	111	52,700	7.7	54	27,100	15
Zn/Fe-DE-1-R	Galv(a)	40'	6'	490	-0.694	879	431,000	1.7	57	402,800	1.8
Zn/Fe-DE-2-R	Galv(a)	40'	34'	485	-0.663	809	392,000	1.9	56	365,200	2.0
EF-T-L	Grid	60'	-	20,290	-0.829	38.8	787,000	0.9	6.2	661,000	1.1
EF-T-R	Grid	60'	-	20,290	-0.647	39.0	791,000	0.9	6.4	661,000	1.1
EF-B-L	Grid	60'	-	20,290	-0.641	21.6	438,000	1.7	5.4	329,000	2.3
EF-B-R	Grid	60'	-	20,290	-0.815	30.5	619,000	1.2	5.8	501,000	1.5
Fe-EF-1-L	Steel(a)	60'	6'	478	-0.447	96.3	46,000	8.8	68	13,530	30
Fe-EF-2-L	Steel(a)	50'	34'	478	-0.701	62.4	29,800	14	42	9,750	42
Zn/Fe-EF-1-R	Galv(a)	60'	6'	485	-0.865	1013	491,000	1.5	56	464,000	1.6
Zn/Fe-EF-2-R	Galv(a)	60'	34'	485	-0.763	255	124,000	6.0	42	103,000	7.2

(a) Buried coupons

(b) Corrected PR* = [PR (Column 7) - R_s] * Area

Table 18. Summary of field results, site 6, September 1989

No.	Description	Height Base (Feet)	Distance From Wall	Area (cm^2)	Free-Corrosion Potential vs. Cu/CuSO$_4$	Polarization Resistance Ohm	PR Ohm*cm^2	CR um/yr	Soil Resistance Ohm	R$_p$ Ohm*cm2	Corrected CR um/yr
BC-T-L	Grid	20	-	34,290	-0.793	10.3	352,840	2.1	1.9	288,000	2.6
BC-T-R	Grid	20	-	34,290	-0.795	11.5	394,340	1.9	2.1	322,330	2.3
BC-B-L	Grid	20	-	34,290	-0.712	16.1	552,070	1.3	2.0	483,490	1.5
BC-B-R	Grid	20	-	34,290	-0.733	15.2	521,210	1.4	2.3	442,340	1.7
Fe-BC-1-L	Steel	20	6	478	-0.415-	110.9	53,010	7.7	76.5	16,440	25
Fe-BC-2-L	Steel	20	34	475	-0.648	159.4	75,720	5.4	43.5	55,050	7.4
Zn/Fe-BC-1-R	Galv	20	6	482	-0.791	1606.7	774,430	1.0	90.0	731,050	1.0
Zn/Fe-BC-2-R	Galv	20	34	485	-0.830	369.0	179,400	4.2	40.5	159,760	4.7
DE-T-L	Grid	40	-	26,690	-0.685	15.7	419,000	1.8	2.4	355,000	2.1
DE-T-R	Grid	40	-	26,690	-0.655	11.7	312,270	2.4	2.4	248,200	3.0
DE-B-L	Grid	40	-	26,690	-0.682	19.4	517,800	1.4	2.8	443,000	1.7
DE-B-R	Grid	40	-	26,690	-0.662	26.0	694,000	1.1	2.9	616,600	1.2
Fe-DE-1-L	Steel	40	6	481	-0.435	73.6	35,400	11.6	50.5	11,100	37
Fe-DE-2-L	Steel	40	34	475	-0.552	111.2	52,800	7.7	51.0	28,600	14
Zn/Fe-DE-1-R	Galv	40	6	490	-0.532	947.0	464,000	1.6	50.0	439.500	1.7
Zn/Fe-DE-2-R	Galv	40	34	485	-0.598	889.4	431,400	1.7	55.0	404,700	1.8
EF-T-L	Grid	50	-	20,290	-0.588	22.0	446,400	1.7	3.0	385,500	1.9
EF-T-R	Grid	50	-	20,290	-0.589	38.0	771,000	1.0	1.1	748,700	1.0
EF-B-L	Grid	50	-	20,290	-0.593	20.6	419,000	1.8	3.3	351,000	2.1
EF-B-R	Grid	50	-	20,290	-0.573	30.1	610,700	1.2	3.6	537,700	1.4
Fe-EF-1-L	Steel	50	6	478	-0.460	80.7	38,600	10.6	52.0	13,720	30
Fe-EF-2-L	Steel	50	34	478	-0.674	51.4	24,600	16.6	29.5	10,500	39
Zn/Fe-EF-1-R	Galv	50	6	485	-0.594	978.6	474,600	1.6	46.0	452,300	1.6
Zn/Fe-EF-2-R	Galv	50	34	485	-0.714	229.1	111,100	6.7	32.0	95,600	7.8

A summary of results obtained is shown on tables 17 and 18.

(e) Site 5 located on State Highway 44, Station 52 in Corpus Christi, Texas, was constructed with galvanized strips. The structure was eight years old at the time of instrumentation but paving had not been placed over it. Therefore, the upper strip had just 2 ft.(0.6 m.) of soil cover. Data from construction control testing indicated the coarse to fine sand backfill to have physical properties shown on table 19:

Table 19. Physical properties, site 7

Mechanical Properties		Electrochemical Properties	
-3"	- 100%	Resistivity	1800-30,000 ohm/cm
+# 200	- 2 to 14%	Resistivity at test	3500 ohm/cm
P.I.	- 3 to 5	pH	6.5-8.7

Two 16 ft. (4.9 m.) strips were isolated and instrumented in the upper layer of wall reinforcement. Following sectioning of the strip for the purpose of ensuring isolation and removing a 1 ft. (0.3 m.) sample, the two instrumented strips were 10 ft.(3 m.) long and approximately 4 ft.(1.2 m.) apart. In between the two strips, three coupons were buried (galvanized steel, pure zinc and carbon steel). Each coupon was instrumented and all leads were connected to a test box at the base of the wall. A +/-60, or 40 mV and 100 mV scan was used to measure the polarization resistance instead of the more standard +/-20 mV scan. This was required to increase the actual amount of polarization applied to the coupon surface because of the very large IR-drop present for the PR tests involving the coupons.

Any error in the polarization resistance measurement or in the soil resistance measurement will greatly affect the corrected value of the polarization resistance, PR, and therefore, under these conditions, the corrected corrosion rate. This effect is seen for the two measurements made for the galvanized coupon in which one measurement was made with the reference electrode at the base of the wall (usual case) and one measurement made with the reference electrode directly over the coupon on the top surface. The two estimates for corrosion rate following correction for soil resistance were 212 and 61 um/y. This is a much greater fluctuation than would be expected under normal conditions between two measurements. It should be noted that when the soil resistance is such a significant portion of the measured polarization resistance, a minimum of three or four polarization resistance measurements and corresponding soil resistance measurements should be made, and the potential scan for the polarization resistance measurements should be increased from +/20 mV to +/60 mV. In this manner, the larger range of potentials for scanning should provide a means of averaging to obtain a more reliable value for the corrosion rate.

The corrosion rates measured for the structure specimens are similar and represent a relatively low corrosion rate. The corrosion rates of the coupons (steel, zinc, and galvanized) all have a much higher initial corrosion rate than exhibited by the two instrumented structure specimens. The high corrosion rates initially exhibited by the coupons are merely high initial rates of corrosion which decreased with time. The corrosion rate of the structures represents a rate after eight years of exposure.

A summary of results obtained for this site is shown on table 20 with typical data obtained from a site visit reported in appendix A.

Potential Gradients, site 7.

A number of strips were examined for potential gradients along their lengths since they were accessible and showed in some instances significant corrosion. The results are summarized on tables 21 and 22.

Zero ft. corresponds to within 2 in.(5 cm.) of the face of the wall. Strips A, B, D and F have relatively similar potentials and in each case, the appearance of the strips were either totally rusted or have at least local areas of rust colored marks indicating that significant amounts of galvanization had been removed. Strip E has a somewhat more negative potential along its length, and no exposure of carbon steel could be detected. Strip C has the most negative potential and the galvanization appeared to be in very good condition.

To further relate the condition of all strips examined, 1 ft. (0.3 cm.)section of Strips B,C,D,E and Structures 1 and 2 were removed at approximately 4 ft.(1.2 m.) from the face of the wall. Also, a control sample (x) identical to the galvanized coupon was included. These specimens were lightly cleaned, then placed through several chemical processes to remove the various corrosion products found on their surface, and then weight-loss techniques were employed to estimate the average amount of zinc remaining on the surface. These results and a description of each sample are given on table 22.

Some general characteristics of galvanized coatings may be of use in explaining the condition and variation in potentials of these

Table 20. Summary of field results, site 7

Coupon/ Structure	Free-Corrosion Potential V, Cu/CuSO$_4$	Area, cm^2	Polarization Resistance, ohm	PR, ohm * cm^2	Corrosion Rate, um/yr	Soil Resistance, R$_s$, ohm	Corrected PR*(d) ohm * cm^2	Corrected Corrosion Rate um/yr
Structure 1	-0.893	2,743	148	406,000	1.8	50	269,000	2.8
Structure 1(a)	-0.890	2,743	136	373,000	2.0	62	203,000	3.7
Structure 2	-0.888	2,743	161	442,000	1.7	49	307,000	2.4
Structure 2(a)	-0.889	2,743	-	-	-	-	-	-
Steel Coupon	-0.475	230	378	86,940	4.7	350	6,440	63
Steel Coupon(b)	-0.476	230	387	89,000	4.6	350	8,510	48
Steel Coupon(a)	-0.482	230	-	-	-	-	-	-
Zinc Coupon	-0.787	230	460	106,000	7.0	420	9,200	81
Zinc Coupon(c)	-0.787	230	464	107,000	7.0	420	10,100	74
Zinc Coupon (a)	-0.792	230	-	-	-	-	-	-
Galvanized Coupon(c)	-0.891	352	275	96,800	7.7	265	3,520	212
Galvanized Coupon(a)	-0.896	352	305	107,000	7.0	270	12,300	61

(a) Reference cell directly over coupons and instrumented structure specimens.

(b) A ± 60mV was used to measure PR instead of the standard ± 20mV scan.

(c) A ± 40mV was used to measure PR instead of the standard ± 20mV scan.

(d) Corrected PR* = [PR (column 4) - R$_s$] * Area.

Table 21. Potential gradients, site 7

Distance From Face Of Wall (Feet)	POTENTIAL					
	A	B	C	D	E	F
0	-0.388	-	-0.692	-	-0.548	-0.407
1	-	-0.558	-	-0.591	-	-
2	-0.602	-0.647	-0.921	-0.668	-0.782	-0.703
3						
4	-0.682	-0.670	-0.011	-0.674	-0.822	-0.690
5						
6	-0.705	-0.732	-1.021	-0.668	-0.857	-0.712
7						
8	-0.712	-0.712	-1.013	-0.685	-0.877	-0.710
9						
10	-0.691	-0.686	-1.038	-0.701	-0.853	-0.718
11						
12	-0.736	-0.721	-1.030	-0.684	-0.862	-0.717
13						
14	-0.704	-0.692	-1.022	-0.684	-0.870	-0.720
15						
16	-0.708	-0.698	-1.019	-0.695	-0.868	-0.711

A: Local areas of steel corrosion near anchor, with Zn or Zn-Fe alloy covering the majority of the strip. No sample removed.

B: The exposed 18 in. (0.46 m.) portion of the strip is completely rust colored. No zinc remaining.

C: Strip C is next to Strip B. C has no rust color corrosion. Zinc spangle is apparent. Sample removed.

D: The exposed 3 ft. (0.9 m.) portion of the strip is completely rust colored (no galv.). Portion removed shows both areas of red rust and possible zinc coating, unlike sample B above.

E: Strip E is next to Strip D. E has no rust color corrosion and the galvanized layer has a dull gray appearance with no red rust or spangle.

F: Local rust color cossoion area over the first 6 in. (0.15 m.) of strip. Significant zinc corrosion product also is visible. At least some galv. or Zn-Fe alloy remains. No sample removed.

Table 22. Zinc stripping test results, site 7

Strips	Potential	Zinc Remaining (cm)	Remarks
A	-0.682	N/A	
B	-0.670	0	Complete red rust; no zinc remains.
C	-1.011	0.013	No red rust; visible spangles.
D	-0.674	0.006	Sample shows localized areas or red rust; no spangles on remaining zinc.
E	-0.822	0.020	Dull gray; no red rust; no spangle.
F	-0.690	N/A	
S1	-0.890	0.008	Dull gray; no red rust; no spangle.
S2	-0.889	0.011	Dull gray; no red rust; some white corrosion products on surface.
X	-0.896*	0.013	Shiny zinc coating with some spangle.

* Potential of identical specimens buried at the site.

strips. One phenomenon that may be involved in analysis of this data is that zinc coatings lose their characteristic spangle when larger amounts of iron are present in the coating. When this occurs, the coating has a dull gray appearance, similar to the many strips in this study. This higher iron content coating produces a more noble potential under most conditions (sometimes as much as -0.45 V versus $Cu/CuSO_4$). This may explain why sample C (visible spangles) has a much more negative potential than sample E (dull gray finish) though both samples appear to have intact zinc coatings. Excessive iron in the alloy layer is commonly caused by: (1) too lengthy immersion time, (2) excessively high bath temperature, (3) steel composition (high P or Si), (4) steel surface roughness (i.e. high roughness, high iron), and (5) excessive coating thickness.

The data in table 22 shows reasonable agreement with the expected behavior of the zinc coatings. Samples showing red rust (B and D) have the most noble potentials (-0.670 and -0.674 V versus Cu/Cu_2SO_4, respectively). Samples with the dull gray (high iron) coatings have more noble potentials than the one sample with obvious spangles in the coating (C). It appears that all of these factors, appearance, coating thickness, coating composition, determine the level of potential measured and that significant variations from "standard" must be expected even in the same soil.

In summary, even in the same soil/moisture environment, the measured potential is not solely dependent on coating thickness but is probably more dependent on whether any carbon steel is exposed and to some degree composition. Therefore, potential alone cannot determine galvanized layer thickness.

4. Summary of Test Results

The methodology and equipment has been evaluated and demonstrated over a variety of sites. Results obtained have been reproducible and reasonably accurate in determining the level of corrosion activity. Table 23 summarizes the pertinent data and average corrosion rates over the stabilized monitoring phase.

The tests sites have been primarily selected to demonstrate the viability of the developed concepts and demonstrate the applicability of the developed instrumentation. This primary purpose has been successful. Review of the limited data suggests certain preliminary additional conclusions with respect to the corrosion phenomenon associated with soil reinforced structures.

(1) Potential measurements are likely to show considerable scatter and by themselves are not always good indicators of the level of corrosion activity. Substantial additional research is needed to further examine the causes for variability.

(2) Polarization measurements must be corrected for soil resistance each time. No reasonable relationship has been found which would predict when this correction would be insignificant.

(3) The measured corrosion rates by polarization resistance compare favorably with anticipated rates outlined in chapter 2.

(4) Limited data suggests that maximum corrosion occurs near the base and in the back third of the structure. Data with respect to higher corrosion near or at the face is inconclusive from this study, but potential measurements reported by Yannas and at site 7 would support a conclusion that this is also an area of somewhat greater risk of corrosion.(24)

(5) Weight loss determinations obtained from retrievable buried coupons will not generally reflect corrosion activity and rates of corrosion as accurately as electrochemical measurements.

Table 23. Summary of test site results

Test Site Results

Site	Saturated Resistivity ohm/cm	Salts Cl ppm	Salts SO_4 ppm	PR Obtained Corrosion Rates Galv.(1) um/yr	PR Obtained Corrosion Rates Steel(2) um/yr	Remarks
Algonquin Site 4	15,000	0	0			New structure strip reinforcement
Upper				1	10	
Lower				1	10	
Algonquin Site 5	15,000	0	0			New structure grid reinforcement
Upper				1	10	
Lower				1	8	
Sweet Home Road	1,600	--	--	6	3	Existing structure strip reinforcement (5 yrs)
Suny Ramps	40-300	0	2100 2700	900	150 200	Existing structure strip reinforcement (6 yrs)
Maple Ave.	700-2800	400	500	8	70	Existing structure grid reinforcement (2 yrs)
Preston	2800-7500	40	69	2	25	Existing structure grid reinforcement (2 yrs)
Corpus Christi	3500	50	34	4	100	Existing structure strip reinforcement (8 yrs)

(1) Rates are for galvanized strips or grids in place.
(2) Steel rates are on coupons installed during this project.

CHAPTER 6 FUSION BONDED EPOXY

1. General

An effective method of preventing electrochemical corrosion from occurring is the use of coatings of fusion bonded epoxies over the base metal. This industry is now well developed and can produce a variety of coatings.

The coating's effectiveness is governed by its ability to suppress anodic or cathodic reactions which lead to electrochemical corrosion. This ability is governed by the following factors:

- Permeability properties of the coating which prevent access of moisture to the metal substrate. With thick coatings, permeation is reduced to diffusion.
- Barrier properties of coating, hindering ionic transport between anodic and cathodic sites.
- Diffusion properties of the coating limiting transport of oxygen to the coating metal interface.

The selection of an appropriate coating is therefore predicated on its having the best combination of properties to limit damage by these factors and yet to be sufficiently flexible for its intended use. In general terms, the lifetime of a coating can be expressed according to the predicted percentage annual penetration of moisture per unit thickness. Pipeline companies currently estimate the life of epoxy powder coatings when supported by cathodic protection to be up to 40 years. No current estimates are available for non-cathodically protected installations.

Two basic processes are involved in determining the ability of a coating to prevent any moisture reaching the metal surface.(25) The first is the ability of the coating to absorb moisture with or without any physical modification to its properties, and second is the permeation rate of moisture vapor through the coating.

Water absorption is normally measured by immersing a weighted film of coating in water for at least 24 hrs. The resulting water absorption should be as low as possible between reported ranges of 0.3 to 1.5 percent. Permeability of coatings may be measured by ASTM D570 with acceptable permeability considered to be less than 2 gr. per mm per meter square for 24 hours.(26)

Oxygen diffusion rates should be sufficiently low to support minimal rates of corrosion. The literature surveyed presents no guidance as to quantitative limits.

Barriers to electrochemical corrosion are generally measured by electrical resistivity (ASTM D-1000) where as a general rule, it is estimated that 10^{10} ohms/cm is sufficient to protect mild steel from the effects of electrolytic corrosion.

Cathodic disbondment under accelerated conditions is measured by ASTM G-8-79. The test period however should be extended to a minimum of 9 months. The relevance of this test to non-cathodically protected structures is questionable, but can be used to compare coatings of the same class.

The widely used 3M-213 coating does not necessarily possess all of the optimum properties for in-ground service, even among the available 3M epoxy products, as this formulation is not widely used by pipeline companies for in-ground service. It is however, based on published test properties, a reasonable compromise between excellent flexibility which may be required for product handling and generally acceptable moisture absorption and disbondment characteristics. The widely used 206N product for pipeline service has better resistance to cathodic disbondment but does not possess the flexibility of 213.

The scope of this research project is not to select the most appropriate coating for use in soil reinforcement applications, but rather to evaluate the potential performance of the widely used 3M, 213 fusion bonded epoxy coating with particular emphasis on potential propagation of corrosion from areas damaged during construction and to determine the most appropriate coating thickness to mitigate construction damage.

Coatings in these test programs were applied in strict conformance with methods and qualification criteria outlined in AASHTO-M-284 except that coating thickness was varied to determine its propensity to undercutting or damage due to backfill operations.

2. Laboratory Tests

Qualitative laboratory tests can be used to evaluate disbondment under accelerated conditions as an index to relative performance, for various reinforcement geometries and coating thicknesses. For this purpose, Fog Spray Chamber Test (ASTM B-117) is commonly used. Results of the test series conducted are shown on table 24.

Table 24. Summary of fog spray tests

Reinforcement Type	Coating Thickness	No Holidays Hrs. to Disbondment	With Holidays Hrs. to Disbondment
Strip	10 mils	>9700	1500
Strip	14 mils	>9700	1500
Strip	18 mils	>9700	1500
Grid	10 mils	9000	1500
Grid	14 mils	>9700	1500
Grid	18 mils	>9700	1500

These qualitative results for durations well in excess of the normal 3000 hrs. indicate that coatings of a minimum thickness of 14 mils, with no intentional defects are effective barriers to disbondment. Where defects in the coating are present, disbondment occurs at 1000 to 1500 hr. regardless of coating thickness. Grid reinforcement showed staining at welded corners as early as 1000 hr., but no disbondment occurred as a result.

A parallel series of accelerated corrosion tests have been performed in corrosion cells on flat resin bonded epoxy specimens intentionally flawed to study undercutting phenomena and its propagation.

The independent variables examined were coating thickness, holiday sizes, and soil type. Two coating thicknesses 10 and 18 mils, two holiday sizes 0.84 and 0.34 cm in diameter, and two soils Soil TTX and Soil SLA comprise the matrix of conditions examined. Each cell contained five identical holidays. The moisture contents used, based on percent of saturation, were held to 65 percent saturation for Soil TTX and 57 percent for Soil SLA.

The coated specimens were initially exposed for 67 days anodically polarized to produce a 3,050 um/yr corrosion rate. This would provide about 560 um of thickness loss during this initial active corrosion period. After this initial high corrosion rate period, the cells were permitted to freely corrode for 115 days. The purpose of the freely corroding exposure was to permit more natural action of local cell attack for undercutting than may be obtained during the anodically polarized experiments. Corrosion rates estimated by polarization resistance during the freely corroding period indicate corrosion rates of 50 13 um/yr for all but the "Soil SLA, 0.34 cm. diameter holiday, 10 mil thick coating" and the "Soil TTX, 0.34 cm. diameter holiday, 18 mil thick coating" conditions. These two exceptions exhibited a corrosion rate of 600 and 250 um/yr, respectively. Following the freely corroding period, the specimens were again anodically polarized to produce a 3,050 um/yr corrosion rate for a period of 9 days.

Soil properties are shown on table 25. Results of the measurements for the amount of disbonding that occurred for each of the four holidays on each specimen are shown on table 26. The amount of disbonding was measured as the largest diameter for the disbonded region associated with each holiday (disbonded diameter). The actual holiday diameter was subtracted from the disbonded diameter to provide a measure of the bonded length. Mean values and standard deviations calculated for various groups of data to examine the effects of coating thickness, holiday size and soil condition are presented on table 27. From the data, it is seen that the 10 mil thick coating has a slightly greater disbonded length than the 18 mil thick coating, the 0.84 cm. holiday has a slightly greater disbonded length than the 0.34 cm. holiday, and Soil TTX produced a slightly greater disbonded length than Soil SLA. All of these trends are based on small differences in the mean values for the disbonded length. It is clear from the large standard deviations that significant overlap of the data occurs and that no significant differences between coating thickness, holiday size and soil type can be established. In fact, a very large disbonded length with two holidays for the Soil TTX condition with a coating thickness of 10 mils and a holiday diameter of 0.84 cm. affected all of the above trends that were observed.

From this data, it appears that undercutting of coatings in soils does occur in areas damaged prior or during installation. However, the variables of coating thickness, holiday size and soil type did not have a significant effect on the degree of disbonding that occurred in these experiments. This conclusion is only true for the range of conditions examined in these tests, and for the 3M-213 fusion bonded coating. Other formulations of epoxy with known better resistance to cathodic disbondment should be similarly tested in order to assess relative performance.

3. Burial Tests

No field retrieval data exists in the literature to assess condition of buried fusion bonded epoxy specimens in soils not cathodically protected.

Table 25. Soil properties,epoxy cell tests

Property	Soil TTX	Soil SLA
pH	7.9	5.2
Cl	85 ppm	63 ppm
SO_4	41 ppm	11 ppm
HCO_3	419 ppm	109 ppm
Soluble Salts	684 ppm	304 ppm
Resistivity (Saturated)	3,700 ohm*cm	15,600 ohm*cm
Sand	68%	59%
Silt	17%	22%
Clay	15%	19%

Table 26. Data for disbonded coating experiments

Specimen	Coating Thickness mil	Holiday Diameter, cm	Disbonded Diameter No. 1, cm	Disbonded Diameter No. 2, cm	Disbonded Diameter No. 3, cm	Disbonded Diameter No. 4, cm	Disbonded Length[(a)] No. 1, cm	Disbonded Length[(a)] No. 2, cm	Disbonded Length[(a)] No. 3, cm	Disbonded Length[(a)] No. 4, cm
Soil TTX - 184	18	0.34	0.74	0.69	0.69	0.58	0.40	0.35	0.35	0.24
Soil SLA - 183	18	0.34	1.43	1.11	1.36	0.51	1.09	0.77	1.02	0.17
Soil TTX - 182	18	0.84	1.14	2.06	1.36	1.31	0.30	1.22	0.52	0.47
Soil SLA - 181	18	0.84	1.00	1.69	1.74	1.41	0.16	0.85	0.90	0.57
Soil TTX - 104	10	0.34	0.96	1.16	1.12	0.93	0.62	0.82	0.78	0.59
Soil SLA - 103	10	0.34	0.86	0.77	0.89	0.81	0.52	0.43	0.55	0.47
Soil TTX - 102	10	0.84	1.55	0.93	2.71	3.16	0.71	0.09	1.87	2.32
Soil SLA - 101	10	0.84	1.35	1.22	1.59	1.04	0.51	0.38	0.75	0.20

(a) Disbonded Length = Disbonded Diameter - Holiday Diameter

Table 27. Statistical analysis of data

Data Base	$\bar{x}$,(a) cm	σ,(b) cm
10mil Coating/0.34cm Holiday	0.60	0.13
10mil Coating/0.84cm Holiday	0.85	0.75
18mil Coating/0.34cm Holiday	0.55	0.34
18mil Coating/0.84cm Holiday	0.62	0.32
10mil Coating-All Data	0.72	0.56
18mil Coating-All Data	0.59	0.33
0.34cm Holiday-All Data	0.57	0.25
0.84cm Holiday-All Data	0.74	0.59
Soil SLA-All Data	0.58	0.28
Soil TTX-All Data	0.73	0.58

(a) mean value
(b) standard deviation

Limited data has been developed based on laboratory burial tests of 10 mil fusion bonded epoxy coatings.(27) Burial in laboratory controlled soil boxes containing five soil types characterized to vary from mildly to very aggressive was made with results available for up to seven years of exposure. Performance has been generally quite good. In the most aggressive soils, limited blisters and subsequent adjacent disbondment has been noted. In the larger disbonded areas, general corrosion attack was evident.

It is not evident from these limited results, whether the disbondment occurred due to poor adhesion to an unclean substrate, or in areas of very thin coating or by other mechanisms, or by any combination of the above. The performance is however, far superior to that of galvanized coatings in aggressive soils over the same time period.

4. Construction Damage Tests

The limited laboratory tests have indicated that good performance of fusion bonded epoxy coatings can be anticipated if construction damage can be limited or eliminated.

To quantify damage, field tests were conducted using nominal coating thickness of 10, 14, and 18 mils for both strip and grid configurations in conjunction with two limiting backfills, a coarse 3 in. (7.6 cm.) gravel and a coarse to fine sand, as shown on figure 24.

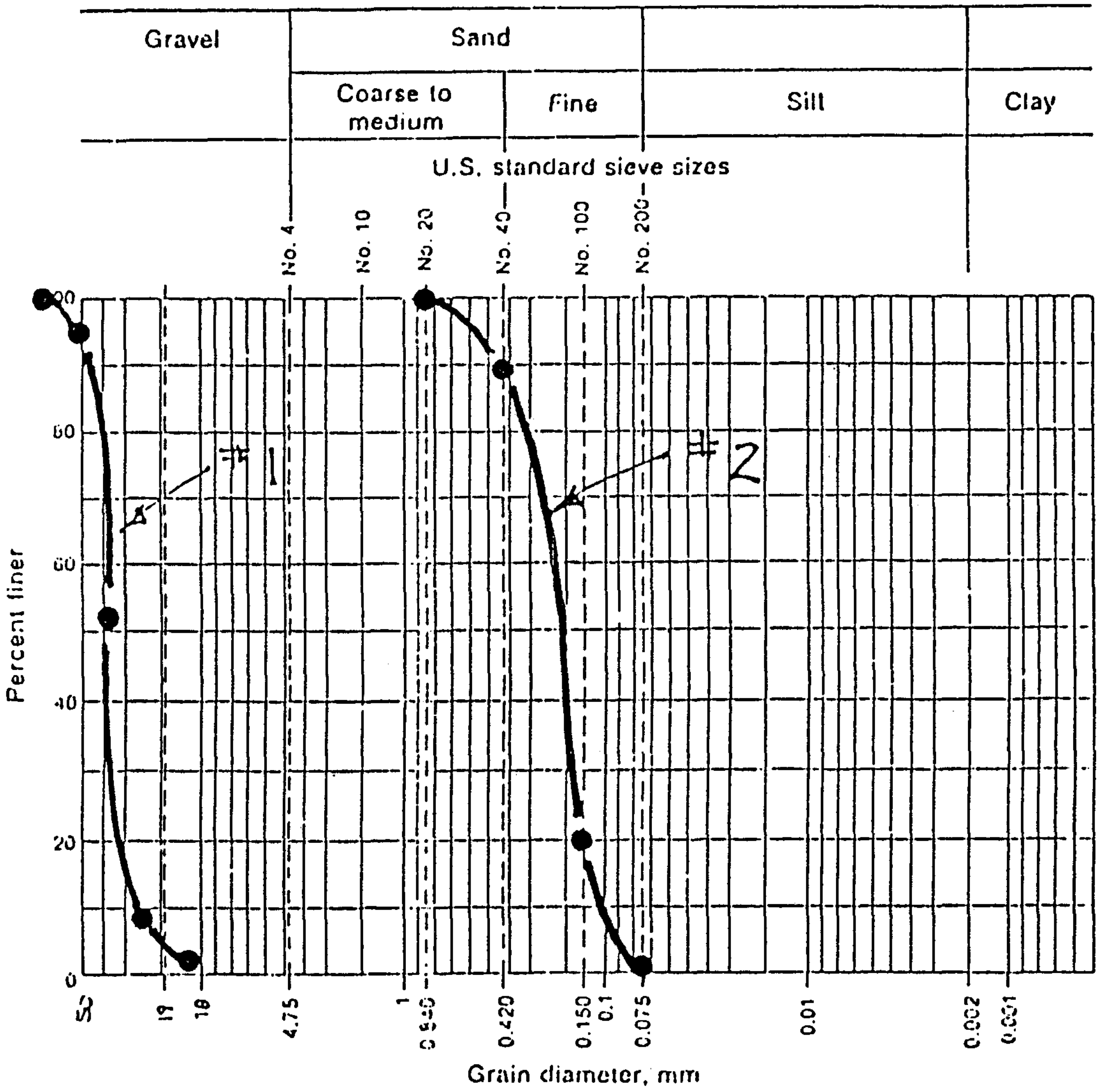
The test was performed during construction of reinforced soil walls at LR 1010, Section 500, Philadelphia, PA. Placement of the fill was by end dumping from 18,000-lb.(8200 Kg.) axle dump trucks. Fill was spread by a DH-4 dozer and compacted by a 15-ton (13,600 Kg.) vibratory roller making approximately 10 passes on the compacted 10 in. (25 cm.) lift. These construction conditions represent the most severe placement and compaction conditions for actual reinforced soil system construction.

Prior to field testing, coating thickness was measured at 6 in. (14 cm.) intervals along with strip or grid intervals and any flaws in coating noted with an electrically activated detector. The same procedure was used after the reinforcements were excavated.

Based on these tests, the relationship between coating thickness and construction damage for the limiting backfill conditions was developed and is shown on figure 25.

Review of data obtained from these tests suggests the following:

(1) Coatings of uniform thickness and quality for grid reinforcements are difficult to achieve at joints.



Visual soil description #1 GP (POORLY GRADED GRAVEL) GNEISS OR GRANITE
#2 SP (POORLY GRADED SAND) ANGULAR QUARTZ

Figure 24. Particle size distribution curves of backfill soils used in the two test sites

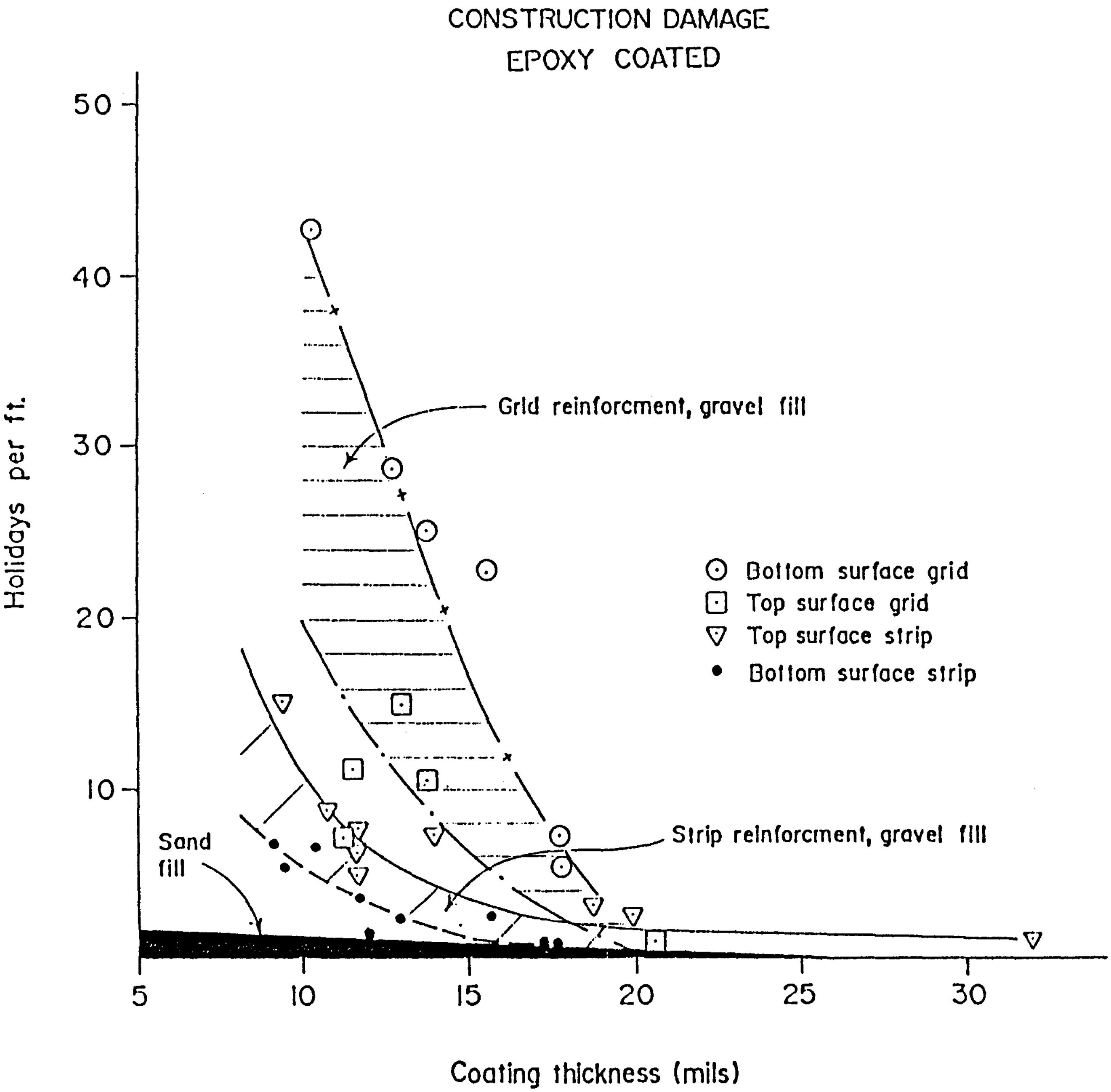


Figure 25. Summary of construction damage on resin bonded epoxy coated reinforcements

(2) Coatings of uniform thickness for strip reinforcement are difficult to achieve and significant coating variation on each strip should be anticipated.

(3) Maximum or D_{85} backfill size is the most significant variaable in causing damage.

(4) Thicker coatings significantly reduce construction induced damage.

(5) Minimum coating thickness of 16-18 mils are recommended in conjunction with the normally specified select backfills which contain maximum sizes of up to 6 inches.

5. Conclusions

The preliminary data available suggests that fusion bonded epoxy coatings should perform significantly better than galvanized coatings even in aggressive soils if construction damage is limited by a thick coating and maximum backfill size reduced to less than one-half in.(3.8 cm.)

No reliable estimate of the life of the coatings can be made at this time. It, however, would seem prudent to assume a maximum life on the order of 20 years, in all environments, in light of the pipeline industry estimate of 40 years life when cathodically protected. Sacrificial metal should be provided based on carbon steel loss rates for service beyond 20 years.

Significant additional research is necessary to further define a credible life expectancy of fusion bonded epoxy coatings, and the variability of the coating process. The main focus of this research should be field retrieval of coated reinforcements from in-service structures.

Chapter 7 DURABILITY OF GEOSYNTHETIC REINFORCEMENTS

1. General

Due to economic advantages and perceived inert state, the use of polymeric reinforcements in soil reinforced structures is increasing. Because of their relatively short period of use, there are uncertainties as to their durability with respect to maintaining design properties after exposure to construction stresses and during exposure to an in-soil environment over the anticipated design life. Potential degradation of polymeric reinforcements with time (aging) will depend on the specific polymer, configuration of the reinforcements and the environment to which it is exposed.

The design of any structural member is predicated on determining an allowable stress throughout the anticipated life of the structure. The long term tension-strain characteristics of polymeric reinforcements are influenced by creep, aging, UV exposure, chemical and biological effects, construction site damage and variations in the manufacturing process. To integrate these factors, Task Force 27 of AASHTO-AGC-ARTBA has recommended that the allowable stress be obtained by evaluating partial factors of safety which are focused on each phenomena which may negatively impact the polymer's performance.(53)

The main polymers currently used for reinforcements include polypropylene, polyester and polyethylene. Other polymers that may be considered, include nylon, fiberglass and aromatic polyamides, such as Kevlar. The final form of the polymer and its corresponding reaction to its environment may vary considerably, depending on the plastic formulations, additives used in the composition and the methods of processing the polymer into its final form (fibers, filaments and subsequent fabric for geotextiles or joined drawn strands in the case of geogrids). Key physical factors in either final form appear to be the molecular weight, density, and thickness of the final polymer element (e.g. fiber, filament or strand). The method of manufacture for geosynthetics, woven heat bonding or needle punching for geotextiles and extruded, welded chemical or adhesive bonding of strands for geogrids may be a factor for short-term construction durability. The manufacturing process does not appear to be a significant factor in relation to long-term aging, except where chemicals or adhesives are used for bonding the material elements. The various types of construction and the variability of the resulting products are covered in the literature.(28,29,30)

The principal aging factors in a soil environment include temperature, moisture, and chemical and biological environment. Certain specific soil environments, in addition, are extremely aggressive and may be unfavorable to certain types of polymers. Rankilor and Van Zanten have identified the following:(28,31)

- . Acid Sulphate Soils - characterized by low pH and considerable amounts of CL^{-1} and SO_4^{-2} ions. For instance, in the U.S. pyritic soils in the Appalachian region would qualify.
- . Organic soils - characterized by relatively high organic contents and susceptibility to microbiological attack. Dredged fills often contain significant organic content.
- . Salt Affected Soils - in areas of seawater saturation or in dry alkaline areas as the southwestern United States.
- . Ferruginous Soils - containing $Fe_2 SO_3$.
- . Calcareous Soils - in dolomitic areas.
- . Soils containing copper and manganese.
- . Modified Soils - soil subject to deicing salts or lime stabilized.

The typical environment to which polymeric materials may be exposed is difficult to define. Consideration should be given to the following range of environments:

- . Stressed conditions at levels of 10 to 25 percent of ultimate strength.
- . Temperature range of 0°F to 100°F (18°C to 38°C)
- . Humidity range of 25 to 100 percent.
- . Biological Activity (macro/micro).
- . Radiation due to UV exposure at specific site.
- . Chemical activity due to soil constituents or additives such as:

    (a) Hydrocarbons
    (b) Organic acids
    (c) organic bases
    (d) Oxidizing agents

As each of these aging factors or specific soil environments will have a varying degree of effect on different polymers or if such conditions cannot be avoided on a particular project, the polymer must be checked for its compatibility with the environment. The artificial relative resistance of polymers to each specific soil environment is shown on table 28.

Table 28. **Anticipated resistance of polymers to specific soil environments**

	Polymers				
Soil Environment	PETP	PA	PE	PP	PVC
Acid Sulphate Soils	?	X	NE	?	?
Organic Soils	NE	?	NE	NE	X
Salt Affected Soils	?	NE	NE	NE	NE
Ferroginous	NE	?	NE	X	X
Calcareous	X	?	NE	NE	?
Modified Soils	X	?	NE	NE	?

NE = No Effect
? = Questionable Use
X = Not Recommended

The literature quantifying aging losses is sparse, however, evidence exists of losses varying from 10 to as much as 60 percent of initial strength.

2. Durability in Moist Environments

All polymers absorb moisture; however, the degree of moisture absorbed and the processes which may influence degradation vary for different polymers. When moisture is absorbed, two processes may take place, plasticization (moisture absorption) and hydrolysis (moisture reaction).

The plasticization process is simply the absorption of water that generally occurs in all polymers to some degree. As the water enters the polymer network, it has a "lubricating" effect, which enhances the network mobility. The basic effect is usually a minimal loss of modulus and tensile strength and a reduction in glass transition temperature. Plasticization is completely reversed when water molecules are removed.

As polypropylene and polyethylene have almost no affinity for water, absorption has a negligible effect on their strength properties. Plasticization has a greater effect on polyesters and polyamides (nylons) which tend to absorb moisture more readily. Tests on these materials indicate that under the plasticization process, modulus and tensile strength decrease on the order of 5 to 10 percent; however, the effect may be reversed when water molecules are removed.

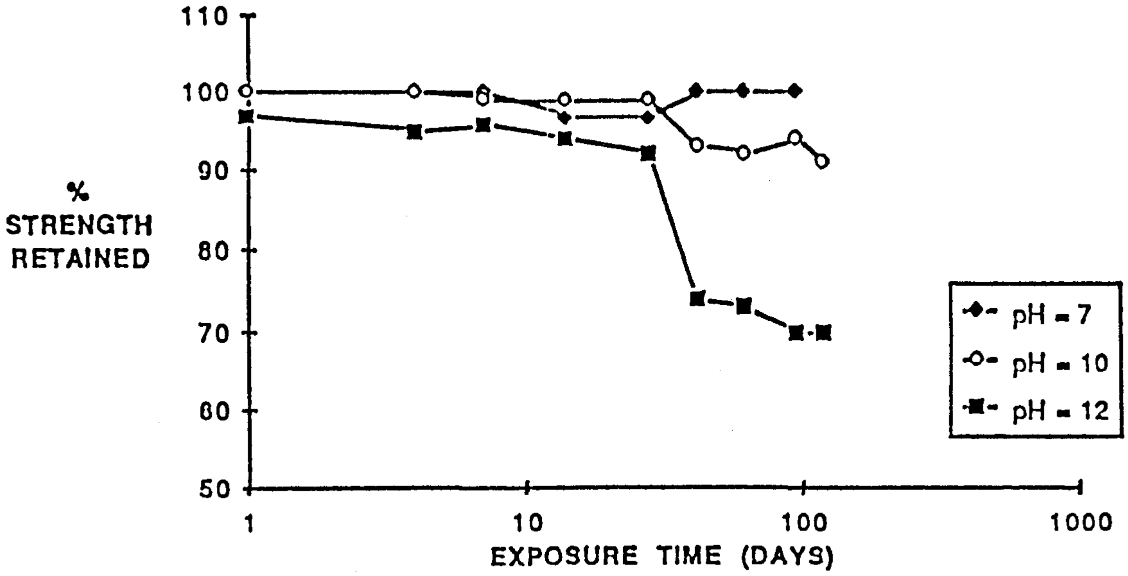
The second and most significant moisture degradation process is hydrolysis or hydrolytic degradation. Hydrolysis occurs when the water reacts with the structure, which in affect reduces the molecular weight and correspondingly decreases the tensile strength. Hydrolysis depends on the molecular structure and has been found to mainly affect ester linkages. The reaction rate is dependent on the rate of diffusion and thus the thickness and density of the material. As diffusion also exponentially increases with temperature, the rate of hydrolysis is highly temperature dependent. Hydrolysis, occurs most rapidly as the glass transition temperature is approached.

Like plasticization, hydrolysis mainly affects polyesters and polyamides. Plasticized polyvinyl chlorides are also affected. The effect is most pronounced near the glass transition temperature, which is at around 70° to 80° C for high molecular weight polyesters.

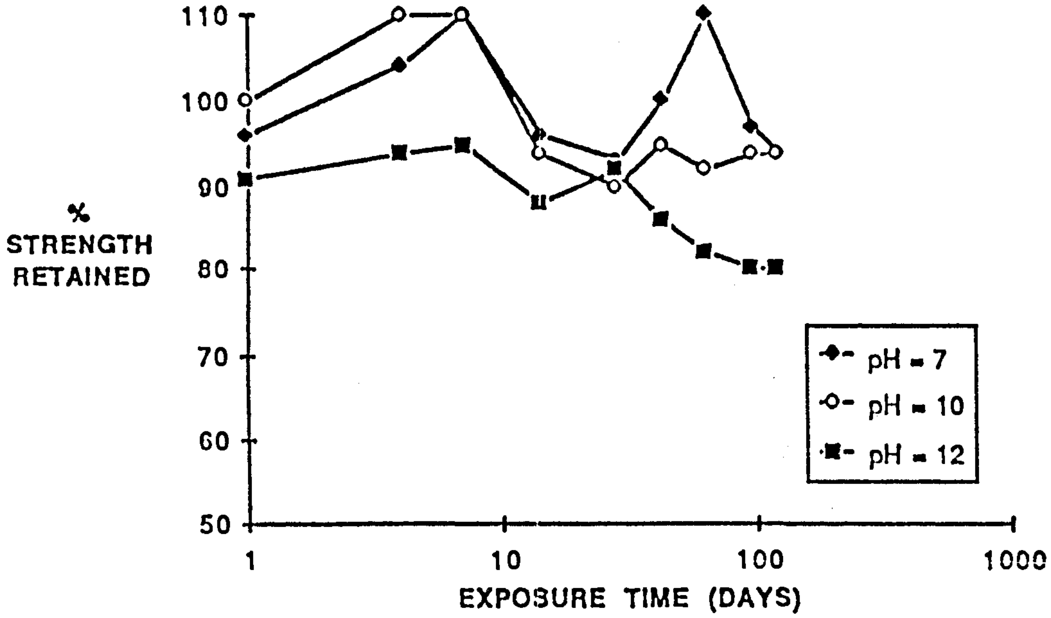
Polyester fibers are plasticized by water, if conditions are such that hydrolysis of the ester group takes place which is a relatively slow process at ambient temperature. The rate of hydrolysis is dependent on temperature and is highly sensitive to acid and base conditions which can catalyze the hydrolysis reaction.(32)

At ambient temperatures, data reviewed by Horz from several manufacturers indicated no loss in strength of polypropylene, polyester or nylon geosynthetics when exposed to water up to 12 months.(33) Other test data indicated a tensile strength loss of 4 percent on high tenacity (high molecular weight) polyester (polyethylene terephthalate) fibers stored at the bottom of the North Sea for over 12 years.(34) This would represent a lower limit because of the low oxygen content and low temperature at the test sites.

A recent review by ICI concludes that hydrolysis induced losses of strength in alkaline soil environments at ambient temperatures for polyester may be as great as 50 percent in 17 years.(35) Under neutral pH conditions the same strength loss is estimated to occur in excess of 50 years and possibly as long as 150 years. The actual degree of strength loss is a function of molecular weight



(a). Polyester Needled Nonwoven Geotextile.



(b). Polyester Heat Set Nonwoven Geotextile.

Figure 26. Response of different polyester geotextiles to high pH liquid

and general hydrophobicity. Short term data developed with respect to strength loss in alkaline solutions shown in figure 26, generally supports the above findings.(36) Koerner, however, cautions that polyesters and their performance may differ markedly depending on their crystallinity, stabilizer content, antidegradants fillers and other ingredients beside the basic resin.(36)

One field case has detailed the loss of strength of a polyester strip (TERGAL) used in a soil reinforcing application.(37) The Poiters structure constructed with TERGAL strips was built in 1971 in France with a silty clayey gravel backfill with a pH of 7.9, resistivity of 14,300 ohm/cm and sulfate and chloride contents of less than 30 PPM. Eleven years later samples of the upper level reinforcements near the concrete facing were obtained and tested for residual strength. Results indicated that warp yarns had lost nearly 50 percent of initial strength and the weft or transversal yarns had lost 20 percent. The latter strength loss was hypothesized as being indicative of hydrolysis losses in a high pH environment, since this direction does not carry the tensile load.

Retrieval samples obtained after 17 years, away from the facing indicated no significant decrease in strength attributable to hydrolysis or other aging phenomena.(52)

3. Durability in Chemical Environments

The chemical environment is an important aging factor, especially considering the aggressive environment that can be formed in soil. The principal mechanisms of chemical degradation have been defined as:(30)

- Metathesis - breaking of carbon to carbon bonds.
- Solvolysis - breaking of carbon to noncarbon bonds in the amorphous (liquid).
- Oxidation - liquid reaction with molecular oxygen.
- Dissolution - separation into component molecules by solution.

Each of these mechanisms result in bond breakage at the molecular wet level, known as bondcision or when under stress, environmental stress cracking. The two primary concerns for geosynthetics are oxidation and bond breakage related to environmental stress conditions. In either case, the end result is a deterioration in the mechanical strength and elasticity of the material which eventually becomes brittle and cracks.

Oxidation breakdown occurs due to heat (thermo-oxidation) and exposure to ultraviolet light (photo-oxidation). Polymers are most susceptible to thermo-oxidation when exposed to high temperatures during processing. However, it can also occur at ambient temperatures, especially in the presence of thermo-oxidative catalytic compounds, such as metallic compounds in the environment. Photo-oxidation only takes place during exposure to ultraviolet light (e.g. sunlight) and is therefore a factor only during storage and construction. Anti-oxidants can be added to the polymer to retard or slow down the oxidation process. The key factors determining the oxidation resistance of the geosynthetic are:(31)

(1) The intrinsic oxidation resistance of the polymer.

(2) The composition of the anti-oxidant packets.

(3) The effect of the thermo-oxidative catalytic compounds in the environment.

(4) The effects of processing on the long term thermo-oxidative resistance.

(5) The resistance of the anti-oxidant additives to leaching by water.

(6) The practical site conditions.

With regard to anti-oxidants, Van Zanten provides an excellent overview of the state of practice.(31)

With regard to specific chemicals that may affect polymers, numerous chemical compatibility tables have been published by geosynthetic manufacturers and others in the polymer industry such as the Plastic Pipe and Wire Insulation Institute.(33)

There are several considerations in using such tables. Test conditions including the exposure time (always short, less than 1 year), temperature, chemical concentration (usually very high) and strength evaluation methods vary between the tables. For any specific polymer, the plastic formulations may vary considerably, especially between industries. Also, the form of the material evaluated (e.g. strap, fiber, block) and the material additives will have an effect. Finally, all results surveyed were carried out in a relaxed, unstressed condition. Under stress, the presence of certain chemicals may have a more pronounced influence on the creep response of a polymer or relaxation of the stress within the polymer, in either case reducing its effectiveness to carry load.

As such, the tables do not provide an indication of service life for a particular product or polymer type, although they provide a screening tool to review the potential susceptibility of polymers to a particular chemical environment.

If the tables show that a polymer is affected by a particular chemical, then additional tests should be performed on the specific products under consideration. If possible, a geosynthetic should be evaluated in a stressed condition and exposed to the actual chemical environment anticipated in the field.

Environmental stress cracking (ESC) is a premature failure that can occur in a polymer material, without chemical change when subjected to concurrent stress and a particular environment.

Environmental stress cracking has been denoted in polyethelenes under stress and exposed to weak acids or bases, solvents or petroleum-based products. The resulting micro-cracks within the material can lead to brittle failure at loads below those indicated as acceptable design values. Highly oriented materials tend to be more susceptible to environmental stress cracking. However, the polymer variables may be adjusted to improve the resistance of highly oriented materials. Wrigley lists the following adjustment for high-density polyethylene (HDPE) which may also apply to other polymers:(38)

- Increased average molecular weight.
- Reduced molecular distribution.
- Reduced crystalline content for bending or increase crystalline content for constant tension.
- Reduced crystallite and/or spherulite size.
- Selective orientation.
- Copolymerization.

To determine propensity to ESC, performance is usually compared in air and in a surfacent solution known to be particularly active in promoting ESC. Tests are carried out in general accordance with ASTM D 2552-69.

Results have been reported for an HDPE (Tensar) geogrid indicating no change in performance in the two environments and therefore concluding that the formulation for that particular geogrid is not affected by ESC.(38)

The resistance of geosynthetics to chemical effects in unstressed states is presently measured in accordance with:

(1) ASTM D-543, "Resistance of Plastics to Chemical Reagents". This is a short term test which should be modified for longer durations. A minimum of 9 months is recommended.

(2) EPA 9090 - which is a similar longer term test at higher than ambient temperatures.

Statistically significant strength losses measured from these short term tests, should disqualify a candidate geotextile for long term in-ground applications, if the chemical condition is anticipated.

The resistance of geosynthetics to outdoor weathering (UV exposure) is measured by:

(1) ASTM D-4355 - "Deterioration of geotextiles from exposure to ultraviolet light" (xenon arc apparatus).

(2) ASTM D-1435 - "Outdoor weathering of plastics".

(3) ASTM B-838 - "Accelerated outdoor weathering using concentrated natural sunlight".

To compensate for exposure during shipping and construction, geotextiles for reinforcement application should be formulated with anti-oxidants or be capable of retaining 95 percent of their initial strength after exposure for 60 days to outdoor weathering consistent with exposure severity at the end use site.

4. Durability in a Biological Environment

There are three forms of microbiological attack, direct enzymatic degradation, chemical production by microorganisms which may result in deterioration of the polymer and polymer-additive degradation. Rankilor provides a good summary of microbiological attack on polymers.(28)

High molecular weight, high density polymers used for geosynthetics, do not appear to be susceptible to direct enzymatic degradation by micro organisms such as fungi and bacteria. Several biodegradability studies have been performed which have shown little loss in strength of any typical polymers used in geosynthetics when exposed to biologically active environments (e.g. mildew) for periods of 1 year or more. There is some indication that very low molecular weight polymers can be consumed especially in the presence of nutrient fillers such as starch.(38,39)

A recent study exposed five commercial nonwoven fabrics to burial in soil over a 7 year period.(40) The soil burial exposure was carried out in a moist organically rich soil maintained at 29 1 C at 85 percent to 90 percent relative humidity at a pH of 6.7. No discernible strength loss was reported for the polypropylene and polyester fabrics but some delamination was observed on the polyamide sheath from the core of a fabric made from a melded bicomponent. An earlier study conducted in West Germany on polyester fabrics encapsulated in meadow and arable soil with a pH 5.8 to 6.3 reported degradation of strength of up to 15 percent after 10 years. It is not however clear that these results could be conclusively attributed to a biological degradation mechanism.

The resistance of geosynthetics to biological effects in unstressed states is presently measured in accordance with:

(1) ASTM G-21 - Resistance of synthetic polymer materials to fungi.

(2) ASTM G-22 - Resistance of plastics to bacteria.

(3) ASTM G-29 - Algae resistance of plastic films.

(4) American Associates of Textile Chemist and Colorists (AATCC) Method 30-81, Fungicides evaluation on textiles; mildew and rot resistance of textiles.

(5) AATCC 24-80 - Resistance of textiles to insects.

Statistically, significant strength losses measured from these relatively short term tests, should disqualify a candidate geotextile for long term in ground applications.

5. <u>Summary of Polymer Durability</u>

Each polymer has particular characteristics related to degradation. Formulation of the polymer, as well as additives and the final form of the material, influence the actual reaction with the specific environment. The key factors for the commonly used polymers are discussed in the succeeding sections, in relation to each of the commonly used polymers. A tentative recommendation is made for reduction in strength due to combined aging factors. This recommendation based on limited data presently available in the literature should be considered a minimum unless long term product specific data is furnished by the manufacturer. Users are encouraged to solicit product specific test results for their projects.

(a) Polypropylene (PP)

Polypropylene with anti-oxidation additives were found to provide good chemical resistance to aqueous solutions of most acids, bases and inorganic salts, even at high concentrations. Polypropylene appears to be subject to attack by strong oxidizing agents, but not by solvents at room temperature. However, polypropylene will absorb chemicals to an extent that depends on temperature and the polarity of the organic material. Absorption increases with temperature and decreasing polarity of the media. The effect of absorption is to cause swelling and a reduction in tensile strength, generally on the order of 10 to 20 percent.

Polypropylene is vulnerable to peroxide, concentrated nitric, sulphuric and chlorosulphonate acids, halogens, halogenated hydrocarbons and certain aromatic hydrocarbons.

Chlorinated hydrocarbons cause swelling of polypropylene at room temperature and some will dissolve polypropylene at 70 C. Polypropylene provides good resistance to microbiological attack, although some degradation could occur due to additives/or plasticizers in the final product.

Except for extreme cases of pH greater than 10 or less than 3, or where hydrocarbons or other oxidizing agents are present, a minimum 20 percent reduction in strength would appear to be appropriate for polypropylene to which non soluble <u>anti-oxidants have been added</u> with respect to aging. This reduction value should be considered a minimum. Design values less than the default values recommended by Task Force 27, should be used when supported by credible long term data supplied by the manufacturers.(53) It should be noted that heavy metals such as iron, copper and manganese and their related salts can accelerate thermo-oxidative processes resulting in greater losses estimated to be as great as a factor of 2 or 3.(31) Polypropylene with no anti-oxidants should be subject to strength reductions equal to the default values recommended by Task Force 27.(53)

(b) Polyester (PET)

Polyesters are susceptible to degradation to chemical classes such as inorganic acids, halogenated organic acids, inorganic and organic bases, benzyl alcohol and halogenated phenols. While polyester is highly resistant to most acids, it is notably affected by strong concentrations of chlorosulfuric, hydrofluoric, phosphorus acid and hydrocarbons. In contrast, it has limited resistance to a wide range of alkalines and a few inorganic salts notably sodium bisulfide and ammonium sulfide. Fertilizers which form acid or bases can lead to varying amounts of degradation.

Polyester is slightly attacked by benzyl alcohol and tetrachclorethane at room temperature. Polyester appears to be resistant to fuel and bituminous materials. There continues to be largely unanswered questions concerning the rate of degradation of polyester due to hydrolysis. However, most of the data which indicates significant reduction comes from tests on low molecular weight polyester. Tests on high molecular weight, high density polyester show a less significant strength loss with time.

There also appear to be some questions as to microbiological attack on polyester. Again, most of the data which indicate the greater degradation has been found for low molecular weight polyester. Soil burial tests on high molecular weight polyethylene terephalate (PET) type polyesters from several studies indicates little to some deterioration with time.(41)

Caution is advisable in using polyester in high pH soils (pH greater than 10).

A minimum strength reduction of 50 percent for high molecular weight polyesters should be used unless the manufacturer can supply long-term credible data in support of other values. Low molecular weight polyesters should not be used in soil reinforcement applications. In the absence of long-term credible data the default values recommended by Task Force 27 should be used.(53)

(c) High Density Polyethylene (HDPE)

High-density polyethylene with anti-oxidant additives is highly resistant to most ambient environmental conditions. Polyethylene was found to have better resistance to oxidizing agents than polypropylene. However, like polypropylene, polyethylene is susceptible to aromatic and aliphatic hydrocarbons. Also, polyethylene is highly susceptible to degradation by halogenated hydrocarbons. Hydrolysis does not appear to be a factor with polyethylenes. High density polyethylene materials are susceptible to environmental stress cracking; therefore, the final product must be designed to be stress-crack resistant, and information to that effect should be supplied by the manufacturer. Polyethylene was found to be highly resistant to microbiological attack, although the information is for high density (high molecular weight) polyethylene materials.

The same information may not apply to low or medium-density polyethylenes.

A minimum 10 percent aging strength reduction factor would appear appropriate for high density polyethylene (HDPE) under ambient conditions when ESC data is available and supports this minimum reduction factor. In the absence of long-term credible data the default values recommended by Task Force 27 should be used.(53) Low density polyethylene (LDPE) should not be considered for reinforcement applications.

(d) Nylon (PA)

Only limited information is available on the chemical resistance of nylon, since this material is used only to a very limited extent as a geotextile. Nylon is reported to have a good resistance to aromatic and aliphatic solvents, common automotive oils and fuels, and refrigerants. Nylon is attacked by strong acids, bases, phenol, as well as by aqueous solutions of ferric chloride and zinc chloride. Degradation due to microbiological attack or hydrolysis appears to be significant. Soil burial tests indicate degradation on the order of 20 percent can be anticipated for certain nylon materials in long term applications for the relatively short test times. More information is needed to provide a credible reduction factor in relation to nylons. Until such information is developed, a high reduction factor is recommended, consistent with default values recommended by Task Force 27.(53)

(e) Composite Geosynthetic Reinforcements

For reinforcement applications, composite construction geosynthetics have been developed to associate high strength, low creep behaviors of a given polymer with barrier properties of a second polymer.

To date, these composites have associated an inner core of polyester fibers which have relative high strength, low extension and low creep properties with an outer covering of PE or PVC to prevent hydrolysis due to moisture absorption and construction induced damage.

The efficiency of these systems in preventing moisture absorption of the polyester core is a function of moisture availability, permeation rate of the outer covering and water absorption properties of the polyester core. In resisting construction damage, the thickness and toughness of the outer sheath govern.

Low density polyethylene (LDPE) has relatively high permeation properties suggesting that high humidity would reach the core in a matter of 1 to 5 year.(44) Therefore, the barrier value of the LDPE is rather limited and the composite would behave with respect to hydrolysis losses as if no barrier coating existed.

The permeation rates of PVC vary widely and are a function of formulation and additives. However, within these variations, PVC does not appear to provide significantly superior behavior to LDPE as a barrier of moisture absorption.

Therefore, composite geosynthetic reinforcements should be evaluated based on the aging properties of the inner load carrying polymer and neglecting any short term benefits of the outer protective LDPE or PVC sheath.

6. Construction Damage Strength Losses

(a) Literature Study

Significant loss of strength has been attributed to geosynthetics damage during construction. The level of damage for each geosynthetic is a variable and a function of:

- Weight of construction equipment used for fill spreading.
- Weight and type of compaction equipment.
- Weight and type of geotextile.
- Lift thickness.
- Gradation and angularity of backfill.

Very few controlled tests on geotextiles to assess this important performance characteristic have been made in the past.

The available prior data is generally of an uncontrolled nature arising out of retrieval programs where control test specimens may have not been available or the construction stresses unevenly applied. Loss of strength values for sheet type geotextiles abstracted from the literature are shown on table 29. These are total losses, but since burial time is generally less than 6 years, they are generally attributable to construction damage.

The range of strength loss reported for a wide range of geosynthetics varies between 10 to 70 percent. Insufficient data presently exists to correlate strength loss to type or thickness of reinforcement, or backfill characteristics but a general trend emerges which strongly suggests that extreme damage is associated with coarse angular backfills, spread in relatively thin lifts and compacted with heavy compaction equipment. The most important variables affecting the level of damage appears to be angularity, maximum backfill size used and weight of fabric.

Table 29. Inferred construction damage losses from retrieval tests in the literature(48,49,50,51)

Material	Weight gr/m²	Max. Fill Size in.	Loss of Strength %
Polypropylene	370	1-2	8-50
"	350	3/4	0-12
"	245	1	16-19
"	204	12	12-52
"	136	1-6	6-28
Polyester	500	2	24-45
"	400	1/8-2	21-55
"	300	1-2	10-60
"	250	3/4	12-15
"	220	3/4	31-46
"	170	3/4	5-35
"	128	3/4	10-14
Polyamine/ Polyester	175	1-2	55-65
Polypropylene/ Polyester	170	3/4	5-30
Polypropylene/ Nylon	140	1	20-30

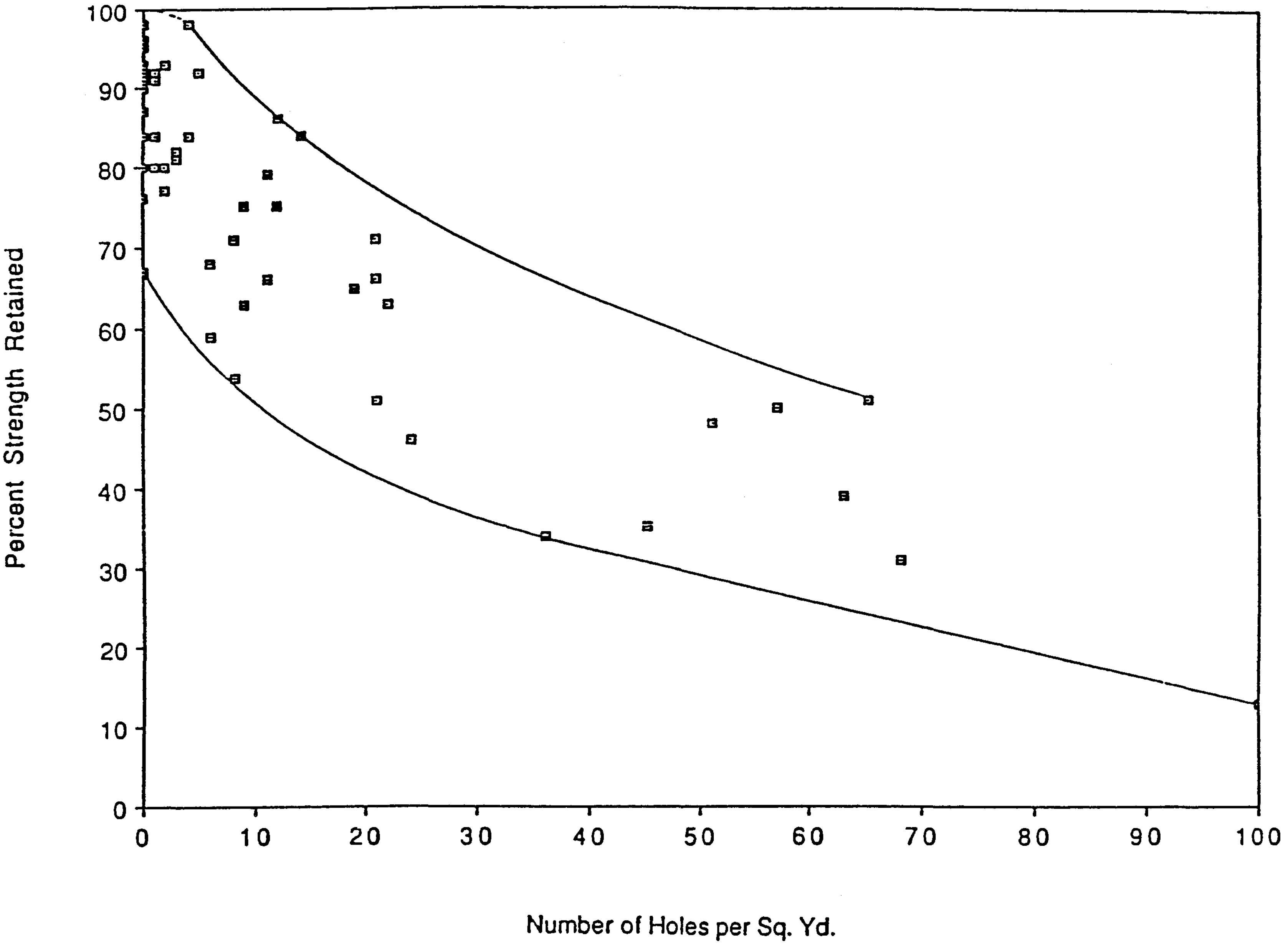


Figure 27. Number of holes vs. strength retained of all tests

Controlled tests were recently performed to assess construction damage for a wide range of geotextiles and geogrids.(42) Measured was both retained strength and hole density as shown on figure 27. Strength loss as expected varied widely from 5 to 75 percent as a function of fabric type and weight. The preliminary conclusions from this work indicate that if all other factors are constant:

(1) Slit film geotextiles are most subject to damage.

(2) Damage decreases substantially with increasing fabric weight.

(3) Minimum fabric weights of 8 oz/yd^2 should be considered regardless of application, based on construction damage survivability. This recommendation is consistent for gravelly sandy fills with maximum sizes in excess of one-inch.

Extensive construction damage testing have been reported on HDPE geogrids.(43) The variables examined were:

. Geogrid thickness.

. Compactive effort and lift thickness.

. Grain size distribution of backfill.

The results indicated the following:

(1) Damage and resulting loss of initial strength increased with decreasing geogrid thickness and weight.

(2) Damage and resulting loss of initial strength increased logarithmically with increasing maximum backfill size as denoted by the D85 size. Backfills with D85 sizes greater than 1 in. (25mm) significantly increased the level of damage with correspondingly greater losses of strength.

(3) Varying compacted lift thicknesses between 6 and 9 in. (15 to 23 cm.) had very little effect on the loss of strength recorded.

(4) Varying compactive effort from four to more than eight passes with a heavy vibratory compactor had only a minor effect on the resulting damage and loss of strength.

(5) The initial tangent modulus as developed from a wide width tensile test, was reduced by approximately 10 percent as a result of construction damage.

Insufficient data of the same quality and extent exists to establish a baseline for strength loss anticipated due to construction-induced stresses for geotextiles, although the concurrent GRI research has shed considerable light on the effect of fabric type and weight.

This phase of the research program was focused on developing:

- A standard controlled field test for construction damage.
- To establish baseline data for geosynthetics currently used in soil reinforcement applications.
- Independently validate previous studies.
- Serve as a model for future studies.
- Confirm strength loss values obtained from the literature.

(b) <u>Model Field Testing Program</u>

The typical reference program developed consists of three tasks:

(1) Preliminary laboratory characterization testing of geosynthetics; focused on geosynthetic strength properties, using the wide-width tensile strength test (ASTM D-4595), in both directions. Grab strength, puncture strength, tear strength and burst strength may be performed to relate performance to typically available index tests. A minimum of five samples for each test is recommended.

(2) Field placement of geosynthetics as follows:

  - Place and compact 1 ft. (0.3 m.) of soil (same as used to cover the geosynthetic) on a flat, level, relatively incompressible subgrade.
  - Place the geosynthetic with the machine direction perpendicular to the face of a wall or embankment. Geosynthetics should be pulled taut with no wrinkles or folds. Pinning at the corners should be considered to maintain the position. Each adjacent sheet of geosynthetic should be overlapped a minimum of 6 in. (15 cm.) with the upper sheet placed in the direction of soil placement. Total sample size of 20 ft. by 12 ft. (6 by 3.6 m.) should be used as a minimum.
  - Place 8 to 10 in. (20 to 25 cm.) compacted thickness of backfill using a front end loader or a D-4 to D-7 dozer.

- Compact the backfill using a 10 to 15 ton (4500 to 13,600 Kg) vibratory smooth drum roller with a set number of passes. The minimum number should insure compaction equal to at least 95 percent of Modified AASHTO density. As a maximum, 10 passes are recommended.

- Carefully remove the backfill by hand and visually describe any observable geosynthetic damage, including a survey of puncture holes per square yard.

- Select samples of the geosynthetic for testing. Sample selection should be guided by the hole survey to obtain representative samples. A minimum number of 10 samples for each test is recommended.

(3) Laboratory Testing to evaluate construction damage:

Perform the following on a minimum of 10 samples:

- Wide width tensile strength - ASTM D4595, both directions.

- Index tests to relate performance to typically available tests may also be performed.

Grab Tensile Strength - ASTM D-4632
Puncture Strength - ASTM D-3787
Trapezoidal Tear Strength - ASTM D-4533
Mullen Burst Strength - ASTM D-3786

Evaluate the retained strength on the basis of the average results obtained from both directions from the wide width tensile test.

(c) Construction Damage Test Results

The model test program was implemented during construction of soil reinforced walls at LR 1010, Section 500 in Philadelphia, Pennsylvania using two limiting backfills with respect to maximum size of backfill as shown on figure 24. Placement of the backfill was by end dumping from 18,000 lb. (8100 Kg) axle dump trucks. Fill was spread by a DH-4 dozer and compacted by a 15 Ton vibratory roller making approximately 10 passes on the compacted 10 in. (25 cm.) lift. These construction conditions represent upper limit placement and compaction conditions for actual soil reinforced system construction.

The two backfills used are also limiting coarse and fine backfills normally allowed by current specifications and should provide upper and lower limits of anticipated damage.

The results presented in appendix A, detail the retained strength as a percentage of initial strength for all of the index tests performed. All index test averages appear to reasonably track each other. Examination of the standard deviation of test results for exhumed samples in each test indicates that the wide width tensile test results exhibit the smallest standard deviations of the index test performed and therefore should be used as the sole index for calculation of retained strength. The standard deviation of the as received samples, wide width tensile strength in the machine direction was approximately 5 percent and slightly higher on the cross machine direction. Other index tests exhibited somewhat greater comparable percentages in standard deviation in the as received condition.

Since the goal of the study was to quantify a factor of safety for geosynthetic construction damage effects, the inverse of the percent strength retained is shown on table 30 for the geosynthetics tested.

Table 30. Construction damage losses

Geosynthetic Type	**Mass/Unit Area** (oz/yd^2)	**Polymer**	**F.S.** Gravel Fill	Sand Fill
Uniaxial Geogrid	25	HDPE	1.41	1.00
Non Woven Needled	16	PET	1.88	1.14
Non Woven Needled	6	PET	3.45	1.27
Non Woven Needled	4.5	PET	3.00	1.19
Non Woven Heat Set	4/3.4	PP	2.78	1.12
Non Woven Slit Film	6/7	PP	4.35	1.09
Non Woven Monofilament	6.5	PP	3.00	1.05

Elimination of gravel sizes in the backfill will significantly reduce the potential for damage even for the lightest weight geotextiles. For each project, this action involves an economic balance between cost differences in fills and higher allowable strength for the geosynthetic reinforcement used. Complete test results of the program are included in appendix A.

The results for gravel fills are of the same order of magnitude as results recently obtained by Koerner.(42) In addition, significant additional insight has been shed on the role of maximum

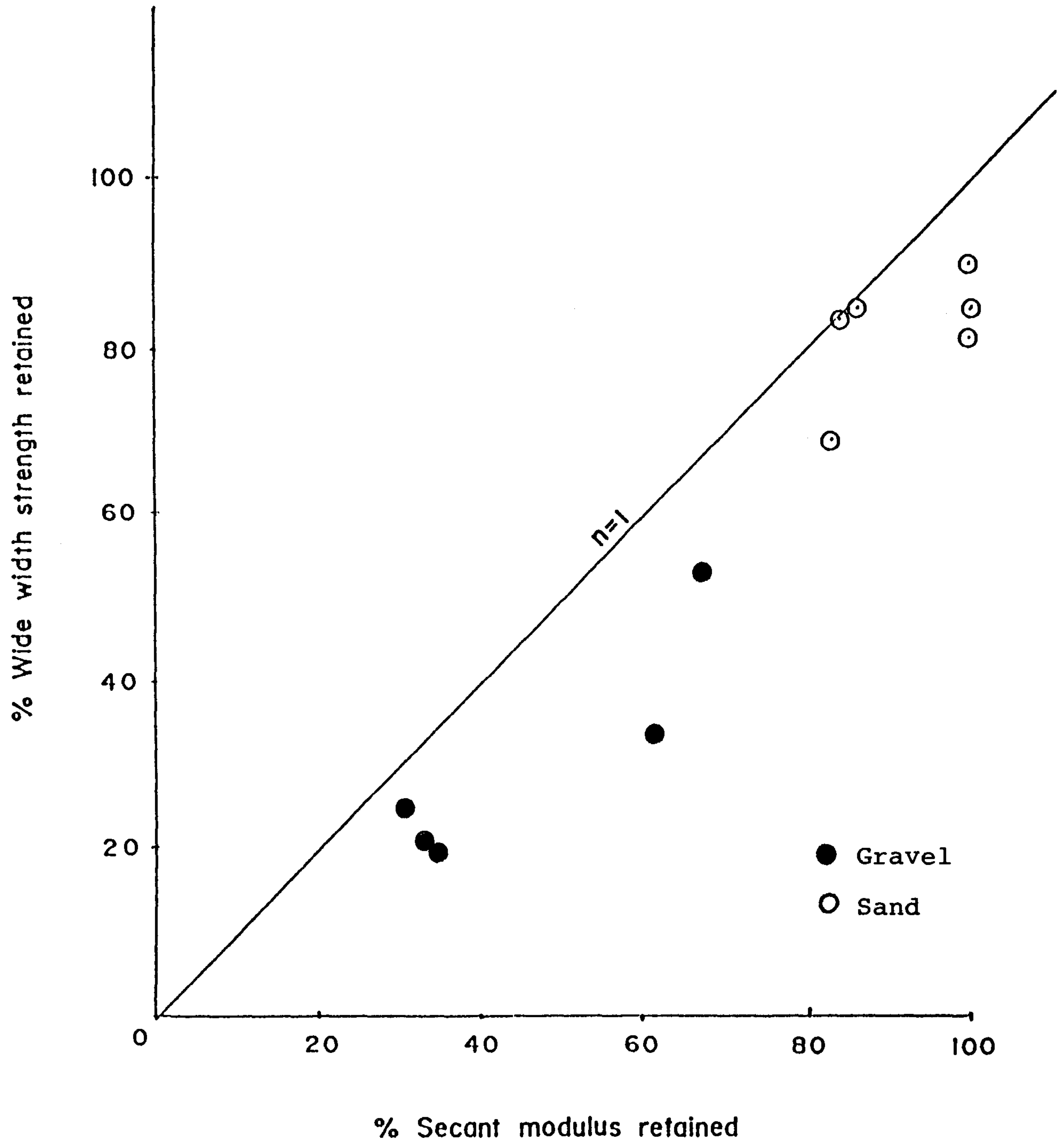


Figure 28. Wide width tensile strength retained vs. secant modulus retained

backfill size. It is clear that even the lightest fabrics, or slit film fabrics, can perform in a relatively satisfactory manner if the maximum or D_{85} size is limited to coarse sand sizes.

Examination of the secant modulus at 5 to 10 percent strain for the as received condition compared to the construction damaged condition, indicates that the secant modulus decreases roughly in proportion to the loss of strength as shown on figure 28.

This finding has significant implications in determining allowable stresses under serviceability criteria.(53) This criteria generally required that the strength at a given level of elongation (5 percent) be considered in developing the allowable stress used in designs.

Table 31 - Wide Width Tensile Tests (machine direction) ASTM D4595
(values in units of lb/in.)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	10	41	483	343	24	40
Nonwoven needled GT	16	6	10	274	148	17	17
Nonwoven needled GT	6.0	5	10	101	21	5	6
Nonwoven needled GT	4.5	5	10	56	14	2	2
Nonwoven heat set GT	4.0	5	10	37	10	3	2
Woven slit film GT	6.0	5	10	192	39	6	12
Woven monofilament GT	6.5	5	10	277	94	5	30

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	10	20	483	573	24	31
Nonwoven needled GT	16	6	10	274	234	17	13
Nonwoven needled GT	6.0	5	10	101	68	5	9
Nonwoven needled GT	4.5	5	10	56	46	2	6
Nonwoven heat set GT	3.4	10	10	39	33	2	5
Woven slit film GT	7.0	10	10	215	182	6	18
Woven monofilament GT	6.5	5	10	277	251	5	16

Table 32 - Wide Width Tensile Tests (cross machine direction) ASTM D4595
(values in units of lb/in.)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	6	10	212	113	3	13
Nonwoven needled GT	6.0	5	10	66	25	4	6
Nonwoven needled GT	4.5	5	10	43	18	6	5
Nonwoven heat set GT	4.0	5	10	40	18	6	4
Woven slit film GT	6.0	5	10	194	49	6	26
Woven monofilament GT	6.5	5	10	192	63	1	19

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	6	10	212	195	3	9
Nonwoven needled GT	6.0	5	10	66	60	4	9
Nonwoven needled GT	4.5	5	10	43	37	6	3
Nonwoven heat set GT	3.4	10	10	44	42	2	3
Woven slit film GT	7.0	10	10	266	289	17	36
Woven monofilament GT	6.5	5	10	192	198	1	9

Table 33 - Grab Tensile Strength Tests - ASTM D4632
(values in units of lb)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	690	339	32	83
Nonwoven needled GT	6.0	10	10	229	98	24	26
Nonwoven needled GT	4.5	6	10	167	47	5	11
Nonwoven heat set GT	4.0	6	10	124	39	5	14
Woven slit film GT	6.0	6	10	299	71	17	29
Woven monofilament GT	6.5	10	10	434	189	14	70

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	690	528	32	51
Nonwoven needled GT	6.0	10	10	229	135	24	14
Nonwoven needled GT	4.5	6	10	167	108	5	14
Nonwoven heat set GT	3.4	10	10	105	79	13	14
Woven slit film GT	7.0	10	10	313	282	10	11
Woven monofilament GT	6.5	10	10	434	402	14	26

Table 34 - Puncture Resistance Tests - ASTM D3787
(values in units of lb)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	256	150	18	92
Nonwoven needled GT	6.0	10	10	102	41	10	38
Nonwoven needled GT	4.5	10	10	80	27	9	22
Nonwoven heat set GT	4.0	10	10	50	21	6	18
Woven slit film GT	6.0	10	10	105	47	26	32
Woven monofilament GT	6.5	10	10	168	60	14	53

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	256	265	18	21
Nonwoven needled GT	6.0	10	10	102	88	10	11
Nonwoven needled GT	4.5	10	10	80	59	9	8
Nonwoven heat set GT	3.4	10	10	51	39	5	6
Woven slit film GT	7.0	10	10	149	145	10	8
Woven monofilament GT	6.5	10	10	168	168	14	16

Table 35 - Trapezoidal tear tests - ASTM D4533
(values in units of lb)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	391	254	27	45
Nonwoven needled GT	6.0	10	10	161	64	12	29
Nonwoven needled GT	4.5	10	10	111	25	11	8
Nonwoven heat set GT	4.0	10	10	64	17	4	10
Woven slit film GT	6.0	10	10	160	50	18	27
Woven monofilament GT	6.5	10	10	73	58	8	28

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	391	380	27	65
Nonwoven needled GT	6.0	10	10	161	69	12	10
Nonwoven needled GT	4.5	10	10	111	55	11	19
Nonwoven heat set GT	3.4	10	10	47	33	6	8
Woven slit film GT	7.0	10	10	143	110	15	14
Woven monofilament GT	6.5	10	10	73	97	8	19

Table 36 - Mullen Burst tests - ASTM D3786
(values in units of lb/in^2)

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	20	906	602	30	145
Nonwoven needled GT	6.0	10	20	320	112	29	50
Nonwoven needled GT	4.5	10	20	261	87	40	42
Nonwoven heat set GT	4.0	10	20	177	87	13	37
Woven slit film GT	6.0	10	20	618	207	20	127
Woven monofilament GT	6.5	10	20	533	225	19	143

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Number Tested		Ave. Value		Standard Deviation	
		As-Rec.	Ex.	As-Rec.	Ex.	As-Rec.	Ex.
Uniaxial Geogrid	25	-	-	-	-	-	-
Nonwoven needled GT	16	10	10	906	857	30	40
Nonwoven needled GT	6.0	10	10	320	273	29	30
Nonwoven needled GT	4.5	10	10	261	185	40	23
Nonwoven heat set GT	3.4	10	10	159	135	12	14
Woven slit film GT	7.0	10	10	736	592	18	45
Woven monofilament GT	6.5	10	10	533	502	19	46

Table 37 - Details of Various Geosynthetic Materials Placed at the Installation Sites

SITE #1 - STONE BACKFILL

No.	Type	Polymer	Weight (oz/yd^2)	Wide width-M(1) (lb/in.)	Wide Width-XMD(1) (lb/in.)	Grab(2) (lb)	Puncture(3) (lb)	Tear(4) (lb)	Burst(5) (lb/in^2)
a	uniaxial geogrid	PE	25	483	-	-	-	-	-
b	nonwoven needled	PET	16	274	212	690	256	391	906
c	nonwoven needled	PET	6.0	101	66	229	102	161	320
d	nonwoven needled	PET	4.5	56	43	167	80	111	261
e	nonwoven heat set	PP	4.0	37	40	124	50	64	177
f	woven slit film	PP	6.0	192	194	299	105	160	618
g	woven monofilament	PP	6.5	277	192	434	168	73	537

SITE #2 - SAND BACKFILL

No.	Type	Polymer	Weight (oz/yd^2)	Wide width-M(1) (lb/in.)	Wide Width-XMD(1) (lb/in.)	Grab(2) (lb)	Puncture(3) (lb)	Tear(4) (lb)	Burst(5) (lb/in^2)
a	uniaxial geogrid	PE	25	483	-	-	-	-	-
b	nonwoven needled	PET	16	274	212	690	256	391	906
c	nonwoven needled	PET	6.0	101	66	229	102	161	320
d	nonwoven needled	PET	4.5	56	43	167	80	111	261
e	nonwoven heat set	PP	3.4	39	44	105	51	47	159
f	woven slit film	PP	7.0	215	266	313	149	143	736
g	woven monofilament	PP	6.5	277	192	434	168	73	537

notes: 1. ASTM D-4595 - "Tensile Properties of Geotextiles by the Wide-Width Strip Method"
2. ASTM D-4632 - "Breaking Load and Elongation of Geotextiles (Grab Method)"
3. ASTM D-3787 - "Puncture Strength of Geotextiles"
4. ASTM D-4533 - "Trapezoidal Tearing Strength of Geotextiles"
5. ASTM D-3786 - "Hydraulic Bursting Strength of Fabrics (Mullen Burst)"

Table 38 - Results from Hole Assessment and Various Strength Tests Performed

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Hole Assessment		Percent Strength Retained					
		Holes/yd^2	Hole Area (%)	WW-M	WW-XM	Grab	Puncture	Tear	Burst
Uniaxial Geogrid	25	5	-	71	-	-	-	-	-
Nonwoven needled GT	16	55	0.57	54	53	49	59	65	66
Nonwoven needled GT	6.0	75	0.99	20	38	43	40	40	38
Nonwoven needled GT	4.5	90	2.9	25	42	28	34	23	34
Nonwoven heat set GT	4.0	55	0.84	28	44	31	42	27	49
Woven slit film GT	6.0	65	0.81	20	26	24	45	31	33
Woven monofilament GT	6.5	60	0.79	34	33	44	36	79	42

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass Per Unit Area (oz/yd^2)	Hole Assessment		Percent Strength Retained					
		Holes/yd^2	Hole Area (%)	WW-M	WW-XM	Grab	Puncture	Tear	Burst
Uniaxial Geogrid	25	0	0	100	-	-	-	-	-
Nonwoven needled GT	16	0	0	85	92	77	100	97	95
Nonwoven needled GT	6.0	0	0	67	91	59	86	43	85
Nonwoven needled GT	4.5	0	0	82	87	65	74	50	71
Nonwoven heat set GT	3.4	0	0	84	95	75	76	70	85
Woven slit film GT	7.0	0	0	84	100	90	97	77	80
Woven monofilament GT	6.5	0	0	91	100	93	100	100	94

Table 39- Test Results of Previous Table Grouped into Various Categories

SITE #1 (Gravel Backfill)

Geosynthetic Type	Mass per Unit Area (oz/yd^2)	Hole Assessment		Percent Strength Retained			Factor of Safety for Installation Damage*
		Holes/yd^2	Hole Area (%)	WW-Ave.	Index-Ave.	All Tests-Ave.	
Uniaxial Geogrid	25	5	-	71	-	71	1.4
Nonwoven needled GT	16	55	0.57	53	60	58	1.7
Nonwoven needled GT	6.0	75	0.99	29	40	37	2.7
Nonwoven needled GT	4.5	90	2.9	33	30	31	3.2
Nonwoven heat set GT	4.0	55	0.84	36	38	37	2.7
Nonwoven slit film GT	6.0	65	0.8	23	33	30	3.3
Woven monofilament GT	6.5	60	0.79	33	50	47	2.2

SITE #2 (Sand Backfill)

Geosynthetic Type	Mass per Unit Area (oz/yd^2)	Hole Assessment		Percent Strength Retained			Factor of Safety for Installation Damage*
		Holes/yd^2	Hole Area (%)	WW-Ave.	Index-Ave.	All Tests-Ave.	
Uniaxial Geogrid	25	0	0	100	-	100	1.0
Nonwoven needled GT	16	0	0	88	92	91	1.1
Nonwoven needled GT	6.0	0	0	79	68	72	1.4
Nonwoven needled GT	4.5	0	0	84	65	72	1.4
Nonwoven heat set GT	3.4	0	0	89	76	81	1.2
Nonwoven slit film GT	7.0	0	0	92	86	88	1.1
Woven monofilament GT	6.5	0	0	95	97	96	1.1

*Based on the average of all strength tests evaluated.

Table 40. Summary of Data for Site 1 I-990 and Sweet Home Road for the August 5, 1988 Field Test

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance[(a)] ohms	Polarization Resistance[(a)] $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[(b)], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.324	228	1,438	327,864	1.2	765	153,444	2.6
Zn Coupon	-0.664	243	1,041	252,963	3.0	765	67,068	11
Galvanized Coupon	-0.603	342	894	305,748	2.4	765	44,118	17
Structure 1	-0.607	2,342	217	508,214	1.5	165	121,784	6.1
Structure 2	-0.530	2,592	372	964,224	0.8	170	523,584	1.4

(a) No correction for soil resistance.

(b) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area.

Table 41 – **Summary Of Data For Site 2 Exit 1 On I-990 (SUNY) For The August 5, 1988 Field Test.**

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance(a) ohms	Polarization Resistance(a) $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance(b), $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.282	228	96.0	21,888	19	35.0	13,908	29
Zn Coupon	+0.407	243	7.99	1,942	380	4.5	848	880
Galvanized Coupon	-0.106	342	66.0	22,572	33	41.5	8,379	89
Structure 1	+0.160	1,434	8.4	12,046	34	6.5	2,725	150
Structure 2	+0.339	1,446	5.2	7,519	54	4.1	1,590	260

(a) No correction for soil resistance.

(b) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area.

* Structure 3 is no longer available for testing.

Table 42 - **Summary Of Data For Site 3 Route 263 And Maple Avenue For The August 5, 1988 Field Test.**

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance[a] ohms	Polarization Resistance[a] $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[b], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.672	123	246.1	30,270	13	200	5,670	72
Zn Coupon	-1.125	243	436.5	106,069	7.0	172	64,273	12
Galvanized Coupon	-1.079	87	2,206	191,922	3.9	485	149,727	5.0
Structure 1	-1.072	3,864	73.4	283,618	2.6	40.5	127,126	5.9
Structure 2	-1.073	4,909	36.3	178,197	4.2	24.0	60,381	12

(a) No correction for soil resistance.

(b) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area.

Table 43 **Summary Of Data For Site 4 Lower Level, Galvanized Strips For The October 21, 1988 Field Test.**

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance ohms	Polarization Resistance $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[(a)], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.329	228	1,885	429,800	0.9	1,720	37,620	10
Zn Coupon	-0.830	243	4,222	1,025,900	0.7	1,670	620,100	1.2
Galvanized Coupon	-0.781	342	2,316	794,400	0.9	920	477,400	1.6
Structure 1	-0.654	3,909	189	738,800	1.0	83	414,400	1.8
Structure 2	-0.663	3,909	228	891,200	0.8	86	555,100	1.3

(a) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area

Table 44 -Summary Of Data For Site 4 Upper Level, Galvanized Strips For The October 21, 1988 Field Test.

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance ohms	Polarization Resistance $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[(a)], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.221	228	2,956	674,000	0.6	2,580	85,700	4.7
Zn Coupon	-0.770	243	7,184	1,745,700	0.4	2,650	1,101,800	0.7
Galvanized Coupon	-0.554	342	4,872	1,666,200	0.4	1,950	999,300	0.7
Structure 1	-0.603	3,909	230	899,100	0.8	115	449,500	1.7
Structure 2	-0.594	3,909	245	957,700	0.8	103	555,100	1.3

(a) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area

Table 45 - **Summary Of Data For Site 5 Lower Level, Galvanized Grid For The October 21, 1988 Field Test.**

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance ohms	Polarization Resistance $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[a], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.279	123	1,761	216,600	1.9	1,340	51,780	7.8
Zn Coupon	-0.890	243	4,443	1,079,600	0.7	1,510	712,700	1.0
Galvanized Coupon	-0.632	87	9,226	802,700	0.9	2,460	588,642	1.3
Structure 1	-0.777	8,467	118	999,100	0.7	52	558,800	1.3
Structure 2	-0.736	8,467	107	906,000	0.8	40	567,300	1.3

(a) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area

Table 46 **Summary Of Data For Site 5 Upper Level, Galvanized Grid For The October 21, 1988 Field Test.**

Coupon/ Structure	Free-Corrosion Potential, V, $Cu/CuSO_4$	Area cm^2	Polarization Resistance ohms	Polarization Resistance $ohm*cm^2$	Corrosion Rate, um/yr	Soil Resistance, ohms	Corrected Polarization Resistance[(a)], $ohm*cm^2$	Corrected Corrosion Rate um/yr
Steel Coupon	-0.295	123	1,812	222,900	1.8	1,440	45,760	8.9
Zn Coupon	-0.773	243	5,360	1,302,500	0.6	1,830	857,800	0.9
Galvanized Coupon	-0.588	87	9,121	793,500	0.9	2,810	549,000	1.4
Structure 1	-0.686	8,467	105	889,000	0.8	43	524,900	1.4
Structure 2	-0.677	8,467	434	3,674,700	0.2	59	3,175,100	0.2

(a) "Corrected" PR = [PR(uncompensated, Column 4) - Soil Resistance] * Area

Table 47 **Summary Of Data For The October 24, 1989 Field Test At Station 52, Corpus Christi, Texas.**

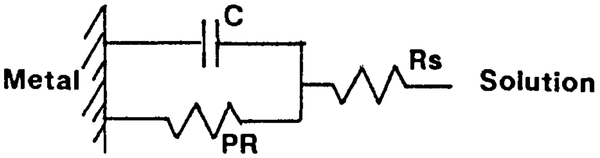
Coupon/ Structure	Free-Corrosion Potential V, $Cu/CuSO_4$	Area, cm^2	Polarization Resistance, ohm	Polarization Resistance PR, ohm * cm^2	Corrosion Rate, um/yr	Soil Resistance, R_s, ohm	Corrected[a] Polarization Resistance, R_p ohm * cm^2	Corrected Corrosion Rate, um/yr
Structure 1	-0.751	2,743	83	227,670	3.3	23	164,580	4.5
Structure 2	-0.725	2,743	62	170,070	4.4	23	106,980	7.0
Steel Coupon	-0.377	230	268	61,640	6.6	253	3,450	118
Zinc Coupon	-0.912	230	485	111,550	6.7	250	54,050	14
Galvanized Coupon	-0.858	252	376	94,752	7.9	167	52,670	14

(a) "Corrected" PR, R_p = [PR (uncompensated, column 4) - R_s] * Area

APPENDIX C : INSTRUMENT MANUAL

INTRODUCTION

Corrosion is an electrochemical process and, therefore, can be studied using various electrochemical measurement techniques. By applying voltages and measuring currents, the corrosion characteristics of a metal\ solution interface can be estimated. The PR MONITOR is an instrument specifically designed to measure the polarization resistance of a corroding interface. The following equivalent circuit for a corroding interface shows the important parameters of that interface.



PR is the polarization resistance which is the resistance of the surface to the corrosion process and is inversely proportional to the corrosion rate. C represents the capacitance of the surface and for an ideally corroding interface with no surface films, C is a measure of the double-layer capacitance of the electrochemical interface. Rs is the solution resistance and is the resistance between the electrochemical interface and the reference electrode which is used to make the potential measurement. The solution resistance is typically neglected for low resistivity environments in which the reference electrode or a Luggin probe can be placed very near the electrode surface. However, for many applications where the solution resistance is large or where it is impossible to locate the reference probe very close to working electrode surface (e.g. concrete and soil environments) Rs can become quite large in comparison to PR. This is important because many polarization resistance, sometimes referred to as linear polarization, techniques based on DC measurements can only measure the sum of PR plus Rs. Therefore, if Rs is large compared to PR, the polarization resistance measured (PR') is much greater than the true value for PR and the corrosion rate estimated can be significantly less than the actual corrosion rate occurring at the surface.

The polarization resistance technique for measuring PR define the polarization resistance as the change in potential divided by the change in current (dE/di). An equation was derived for dE/di that was applicable at potentials very close to the free corrosion potential (±5-20mV). This equation is given as follows:

$$dE/di = \frac{2.3(Ba*Bc)}{(Ba+Bc)i(cor)}$$

i_{cor} is the corrosion rate, B_A is the anodic Tafel constant, B_c is the cathodic Tafel constant, and PR is the polarization resistance defined as dE\di. This equation indicates that for potentials ±5-20mV around the free-corrosion potential, the corrosion rate is inversely proportional to PR. Also, PR is equal to the slope (dE/di) of the linear plot of potential verses current at the free-corrosion potential.

From the above, it can be seen that to measure the polarization resistance requires instrumentation to produce an E versus i plot ±20mV of the free-corrosion potential and the ability to calculate the slope of that curve. There are many measurement schemes that can accomplish the polarization resistance measurement, but most often these schemes would include scanning, or stepping, the potential from -5 to -20mV to +5 to +20mV around the free-corrosion potential while simultaneously measuring the current applied.

The PR MONITOR utilizes a potential control stepping sequence that is completely flexible and programmable by the operator. The programs within the PR MONITOR permit complete freedom in the step size, number of steps, time between each step, and the potential with respect to the free-corrosion potential for beginning the stepping sequence. By providing these selections to the operator, the average scan rate for the polarization resistance test can be controlled. The PR MONITOR utilizes digital feed back for potential control. At the end of the standard polarization resistance measurement cycle, an AC signal is applied between the working and counter electrodes for the purpose of measuring the solution resistance, Rs, value. Referring back to the equivalent circuit for the electrochemical interface previously shown, it is seen that during a high frequency measurement the capacitor acts as a short, permitting the measurement of Rs independent of PR. With the above sequence, PR' (PR + Rs) is measured using standard DC techniques followed by the measurement of Rs by AC techniques. Thereby PR is calculated as PR' - Rs. The PR MONITOR presents the data as PR', Rs and PR. The PR MONITOR also presents the regression coefficient of the linear regression used to calculate the value PR' from the E versus i plot. A regression coefficient of 0.9 or greater indicates a reasonably good fit of the data to the linear plot.

FEATURES OF THE PR MONITOR

Field Worthiness

The PR MONITOR was specifically designed for field measurements but the rugged features built into the PR MONITOR for field work are also ideally suited for laboratory polarization resistance measurements. The front panel is completely sealed to prevent dust, dirt, and moisture from getting in contact with the internal parts of the PR MONITOR. The PR MONITOR is enclosed in a aluminum case to withstand the rigors of field measurements.

Power Supply And Interfaces

The PR MONITOR is capable of a ±12 volt output between the working and counter electrodes and can supply up to 0.5 amps of current. The voltage and current outputs permit the PR MONITOR to be utilized to measure polarization resistance of extremely large structures, as well as small laboratory or field coupons. The PR MONITOR can be powered from either battery operation or 120 volts AC.

A high input impedance electrochemical interface provides a 10^{12} ohm input impedance between the working and reference electrode input. The very high input impedance ensures that the working electrode is not loaded down by connection of the instrument.

Software Features

The PR MONITOR provides an alpha-numeric keyboard with typewriter style character format. This permits comments to be typed in with each experiment. The forty character display prompts the operator for all of the pertinent information needed to perform the test and provides a default or perform last setup for quick and easy repeats of the same measurement schemes. The PR MONITOR provides an RS232 serial interface for down loading data into a PC. The PR MONITOR comes with non-volatile memory to ensure the stored data remains available to the operator even when power is lost to the instrument. The PR MONITOR can store up to 19 polarization resistance runs.

The PR MONITOR can be setup to repeat a given test and automatically store the data. Therefore, the PR MONITOR permits the operator to setup the equipment and make polarization resistance measurements every hour, or day, (the time selection is completely variable) with up to 19 runs being stored in the internal memory.

Solution Resistance Compensation

The PR MONITOR has an high frequency AC generator that permits the measurement of the solution resistance Rs, automatically following the polarization scan. Therefore, the error involved in not compensating for the solution resistance is eliminated. It has been shown that the Rs correction is critical in both soil and concrete measurements, as well as many applications involving two electrode techniques or measurements where the reference electrode can not be placed within a few millimeters of the working electrode surface.

GENERAL OPERATION

The PR MONITOR is microprocessor based instrument that utilizes a digital feed back from the reference and working electrodes to control the potential. The operation of this potential feed back control is similar in most all respects to the more standard operational amplifier potential control potentiostat. Communication between the operator and the microprocessor is accomplished through a typewriter style format keypad and a forty character two line LCD display. The PR MONITOR is user friendly and prompts the operator for all the necessary information to setup and perform a polarization resistance measurement.

External Connections

The PR MONITOR has three electrode connections on the front panel: counter electrode, reference electrode, and working electrode. For standard three electrode technique measurements, the electrode connection is similar to any other electrochemical measurement utilizing a reference electrode. The working electrode input is connected to the coupon or structure for which the corrosion rate is desired; the reference electrode input is connected to the reference electrode being utilized; and the counter electrode input is connected the counter, or auxiliary, electrode, usually an inert electrode such that contamination of the solution does not occur (in instrumented MSE structures, the alternate instrumented reinforcement is used). Internal relays control the connections for the polarization resistance measurement or solution resistance measurement automatically.

Two electrode method measurements can also be performed utilizing the PR MONITOR. Typically, the solution resistance measurement is more critical for two electrode method measurements because a reference electrode is not positioned close to the working electrode and the two electrodes are typically spaced relatively far apart. For the two electrode technique, the working electrode is connected to one of the two electrodes and the counter and reference leads are both connected to the second electrode. All of the measurements are the same as the three electrode technique but the operator must remember to divide the value of PR obtained by two since the potential difference applied to each of the electrodes is actually one half of the applied potential since the electrodes are identical and each electrode undergoes polarization.

Power Connections

The PR MONITOR can be run on either batteries or 120 volt AC power. The PR MONITOR comes with two 12 volt rechargeable gel cell batteries internally connected. A switch on the back panel selects either battery operation, 120 volt AC operation, or battery charging. Measurements cannot be performed during the charging stage. There is an on and off switch on the front panel of the PR MONITOR. Connections to the working, reference and counter electrodes should be performed with the PR MONITOR in the on position. The on position is similar to an isolate position on a potentiostat since the internal program switches the potential control circuit on and off automatically.

Escape Key

The escape key permits the operator to exit at any point of any of the menus or during an experimental run and returns the program back to the initial position in which the PR MONITOR requests "make selection using the blue function keys".

Function Keys

The measurement (RUN), store, recall, and print functions of the PR MONITOR each have there individual keys and are indicated on the front panel as function keys. The purpose of these keys are to permit these functions to be performed easily by the operator without continually referring back to the manual. The run key is used to perform a polarization resistance measurement. Prior to performing each measurement a comment describing the measurement is permitted. The store key is used to store data for an individual run. If a single run is performed and not stored, then that particular experiment is not maintained in the memory of the instrument. If multiple runs are performed at a predefined interval then each of those runs are stored automatically. The recall function permits individual experiment, group of experiments, or all of the experiments in the memory to be recalled to the screen. The print function permits an individual experiment, group of experiments, or all of the experiments in the memory to be printed to either the internal printer or down loaded to a PC through the RS232 serial interface. Each of the individual function keys are described in detail in the following sections.

RUN EXPERIMENT

The purpose of the RUN function key is to set up and perform the polarization resistance experiment. Upon pressing the RUN function key the following display appears:

RUN TEST: Enter comment for this test:

A comment can consist of up to forty characters describing the location, date, coupon number, test number, etc. At the end of the comment press the ENTER key. The following display will appear:

SET UP MENU: Default Last New

This selection permits a test to be performed using all of the default values; the last, or previous, setup; or permits a new test sequence to be defined. Selection is accomplished by entering the first letter of the selection. If either the default (D) or last (L) is selected the display will ask the operator to " make sure electrodes are connected" and to " press enter key to start" the experiment. Upon pressing the ENTER key the experiment will be performed utilizing either the default or the last experimental setup whichever was selected. If at the setup menu, new (N) is selected the following display will be shown:

How many test to run..........[1] :

The default selection (shown in brackets) can be selected by pressing the ENTER key. If multiple tests are desired the desired number up to 19 can be entered upon selecting the desired number and pressing the ENTER key. The following will be displayed:

How many minutes between test [60]:

This will establish the number of minutes between the start of each of the polarization resistance measurements. A maximum of 999 minutes is permitted. Upon entering the minutes between tests the selection sequence will continue. If the "default" or a "1" had been entered to the previous question "how many tests to run", the questioning sequence would pick up at exactly the same question as when a multiple number of tests was selected and the time between tests was selected. Therefore, the following appears on the display:

Number of readings for tests ...[9]:

For example, the default number of 9 permits -20 to +20 millivolt potential scan to be performed in 5mV increments. Any number of readings can be entered here depending on the personal desires of the operator. The simplest polarization resistance measurement would be to enter 2 here and provide a single potential step, e.g. 40mV to provide a reading at -20 and +20mV. Following either pressing the ENTER key for the default number of test readings or entering the desired number, the following is displayed:

Seconds between readings...... [30]:

The time between readings in seconds should be entered here. This will define the average scan rate for the polarization resistance experiment. For example, the default value of 30 seconds and the default value of 5mV gives a 0.17 millivolt per second average scan rate. If the default value of 30 seconds is desired the operator merely presses the ENTER key. If a different value is desired the number of seconds should be keyed in followed by pressing the ENTER key. Upon entering the seconds between readings the following is displayed:

Auto, high, or low resistor A/H/L [A]:

This selection permits either automatic resister selection for measuring current or if the operator thinks that the automatic selection is in error then the operator can select either the high (10,000) ohms or the low (10) ohm measurement resistor. In the PR MONITOR operation a single measurement resistor is selected based on the initial measurement and is used throughout the experiment. The sixteen bit A/D utilized in the PR MONITOR provides a tremendous range of currents to be measured utilizing a single resistor. Because the slope of a linear plot that goes through 0 current is the desired parameter, no loss in accuracy in the polarization resistance measurement is observed by performing the measurement using a single resistance value for measuring current. The default value of automatic resistance selection is possible by pressing the ENTER key or a high (H) or low (L) resistor value can be selected followed by pressing the ENTER key. Upon pressing the ENTER key the following is displayed:

Voltage drop between readings [5] :

This selection determines the size of the potential step in millivolts. The default value is a 5mV potential step (5mV voltage change between readings). A 5mV default value can be selected by pressing the ENTER key or any other millivolts selection may be entered followed by pressing the ENTER key, and the following is displayed:

Potential over E_w to start .... [20] :

This selection establishes the number of millivolts negative (cathodic) to the free-corrosion potential (working electrode potential - E_w) to initiate the test. The default value of 20mV can be selected by pressing the ENTER key or any other overvotage in millivolts can be selected. Upon pressing the ENTER key, the following is displayed:

Solution factor (.5 to 1.5)... [1] :

The solution factor corresponds to a normalized value for the solution resistivity. The default value of "1" has been seen to apply to 80 to 90 percent of the cases examined. The solution factor can be increased above 1 if the desired potential levels are not obtained. For example, if the potential is selected to apply 20mV more negative than the free-corrosion potential to initiate the test sequence, and after the time duration between readings (30 seconds for the default) an overpotential of only 15mV was obtained, then the solution factor can be increased to above 1 to increase the voltage scan rate such that the 20mV over potential is obtained before the measurement is made.

It should be noted that if an experiment is performed and the initial overvoltage of 20mV is not obtained, the potential stepping of 5mV will soon be caught up with and the experiment will resume in its normal fashion. Because potentials and currents are measured simultaneously at the end of each time interval (30 seconds) an accurate polarization resistance is measured even when the -20mV overvoltage is not obtained. It is suggested that for each individual experiment the default value of 1 be selected unless it is otherwise determined that there is a problem. Upon entering the solution factor, the PR MONITOR display will ask the operator to "make sure the electrodes are connected" and to "press ENTER key to start" the experiment. Upon pressing the ENTER key, the PR MONITOR display will indicate that the test is under way ("working"). During the experiment each data point that the PR MONITOR has measured will be shown on the display. For example:

Reading 1 Ref. -0.013V, current 129 uA.

At the end of the pre-defined number of readings and following the high frequency AC measurement of the solution resistance, the value for the total measured resistance PR (includes Rs); the polarization resistance PR; (PR'), and the solution resistance (Rs) will be displayed on the first line the free-corrosion potential (working electrode potential (E_w)) and the corralations coefficient of the linear regression will be displayed on the second line. If the operator wishes to examine the individual data points he can press the ENTER key at this stage and can scroll through the data by continuing to press the ENTER key. Upon finishing the polarization resistance measurement, and solution resistance measurement, the following is an example of the display:

PR = 10,652; PR'= 10,880; Rs = 227
E_w = 0.8454; correlation COEF = 0.989

Press the ENTER key and display shows the following:

Reading 1 ref. -00.866, current 5uA

Press the ENTER key and display reads:

Reading 2 ref.-0.861V, current 30uA

Continue pressing the ENTER key to show all of the data with the final display showing:

Reading 9 ref. -0.824V, current -4uA

Press the ENTER key and the display reads:

Number of tests ....: 1

Press the ENTER key and the display reads:

Minutes between tests .....: 1
Number of readings ....: 9

Press the ENTER key and the display reads:

Seconds between readings ..: 10
mV drop between readings space ..: 5

Pressing the ENTER key returns the display back to the same display as was observed at the end of the polarization resistance measurement. The data can be scrolled through as many times as desired. The operator can exit the program by pressing the ESCAPE key or one of the function keys.

DATA STORAGE

The purpose of the STORE function key is to permit single experimental runs to be stored on a selected basis. That is, the STORE function key must be selected at the end of any polarization resistance run for which the data is to be stored. It should noted that the selection of multiple polarization resistance runs in the experimental setup of the RUN function key automatically stores each polarization resistance test. By making the storage of the data a manual selection, as opposed to storing all data, permits the operator to perform various preliminary trials on different coupons (or structures) without having to store all of the individual runs. This has been found useful in performing field measurements in which preliminary tests to establish the time between readings (average scan rate) for obtaining steady-state data is performed.

Upon pressing the STORE function key the following is displayed:

Using the location __ of 19 to store data.
Make selection using the blue function keys.

The STORE feature stores the last data set into the next available location (1-19). In doing so, the new data set is written on top of an old data set. Therefore, care should be taken so not to store on top of data which a hard copy has not yet been obtained. Once location 19 has been filled the following is displayed:

No more room to store data.
Start replacing data at location 1 y/n:

By answering yes (Y), the new data is stored at location 1. Selecting no (N) brings back the display, "make selection using blue function keys."

RECALLING EXPERIMENTS

The RECALL function key is used to recall data onto the screen for review of the data prior to printing or to recall data when,for whatever reason,it is not desired or possible to print the data. Upon pressing the RECALL function key the following is displayed:

Recall Menu: All One Range Current

Selection of any one of the above four selections can be accomplished by keying in the first letter of the selection: All (A), one (O), Range (R), or Current (C). Keying in an "A" immediately brings to the screen "Location 0" on the top line and the comment associated with "Location 0" on the second line. It should be noted that "Location 0" is always used to store the last experiment (current data) regardless of whether that data had been previously stored. All of the information for "Location 0" can be scrolled through by continuing to press the ENTER key. All locations (0-19) can be scrolled through in this manner.

A selection of One (O) at the Recall Menu is followed by the following display:

Which one ..:

Upon entering the location number followed by pressing the ENTER key, the data stored for that location will appear on the display and the operator can scroll through the data by continuing to press the ENTER key. Following all the data for that location the PR MONITOR will ask the operator to "make selection using the blue function keys".

If the Range (R) is selected back on the Recall Menu the following is displayed:

First location to print ....:

The purpose of these questions is to define the range of locations to be displayed on the screen. The smaller value of the location should be entered, followed by pressing the ENTER key. The display will return with the following:

Last location to print ....:

The operator will key in the last location of data desired followed by pressing the ENTER key and the data will be immediately displayed starting with the smaller location number. The data can be scrolled through by continuing to press the ENTER key until the data for each location has been reviewed. At the end of the data, the PR MONITOR will ask the operator to "make selection using the blue function keys."

If the Current (C) is selected from the Recall Menu, the data in Location 0 is immediately presented. Location 0 always has the current, or last, experimental data set contained in its memory. It should be noted that if the RUN key is selected and a partial experimental set up is keyed in followed by escaping or pressing one of the other function keys, then Location 0 will contain a mixture of the newly entered data as well as existing data from the previous run, i.e. Location 0 always contains the last information keyed in.

PRINTING DATA

The purpose of the Print function key is to provide a hard copy of the data to the operator. Upon selecting the PRINT function key the following is displayed:

Print Menu: All One Range Current

The Print Menu set up is exactly the same as the Recall Menu previously described under Recalling Experiments. The only difference between the PRINT and RECALL function keys is that the RECALL function key displays the data on the screen and the PRINT key provides a hard copy to either the printer (optional) or the RS232 serial interface.

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