Field and Laboratory Characterization of Corrosion Potential in Highway Corrugated Metal Pipe

by

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Abstract

Thousands of metallic drainage structures have been installed by the Kansas Department of Transportation (KDOT) to facilitate proper drainage of highway systems across the state. Several studies were conducted over the past 30 years by KDOT to determine the durability of different corrugated metal pipe (CMP) materials and estimate their performance against the deterioration that occurs due to the electrochemical process of corrosion. These past studies have influenced KDOT policy regarding pipe material, but a method to quickly determine the rate of deterioration, and accurately predict a service life, is still not well defined. With the last comprehensive study performed in 1990 by KDOT, there is now a need to perform a field evaluation to determine the performance of CMPs in Kansas. This research conducted a survey of observed CMP conditions for 80 sites across KDOT districts one and four using a quantitative observational rating system. The goal of the survey was to determine the performance of CMPs in the field. The findings of this study indicate that a 1975 change in KDOT pipe policy has increased the rapid deterioration of CMPs. An additional study was conducted to determine if accurate service life predictions could be made based on chemical and biological characteristics of soil taken near the CMP invert. A method to test the leachate water exposed to the soil sample was created. Laboratory results of four field samples indicated that the rate at which the invert deteriorated corresponded to the total amount of chloride anion mobilized in the leachate over a 72-hour period, along with the standard deviation of pH measured throughout the test. This contradicts most field corrosion tests that only measure field pH and resistivity. The developed method of measuring soil sample leachate may provide a more accurate estimate of the performance of CMP in the sample location.

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Chapter 1 - Introduction

Thousands of metallic drainage structures have been installed by the Kansas Department of Transportation (KDOT) to facilitate proper drainage of highway systems across the state. Past studies have been done in the state of Kansas to determine the durability of different corrugated metal pipe (CMP) materials and the impact of soil/water characteristics on the electrochemical process of corrosion (Stratton, 1989; Stratton et al.,1990; Brady et al., 2016). There is now a need to perform a field evaluation to determine how these structures have performed recently compared to past studies, and develop new ways of measuring how susceptible these structures are to corrosion.

In 1989, KDOT developed a method of measuring how CMPs were performing in the field (Stratton, 1989). This system included a standardized grading scale which was used to rate the conditions of CMPs by visual observation. In total 103 pipes were surveyed by the 1989 KDOT team. This method of surveying CMPs in the field was further refined in a subsequent study by Stratton et al. (1990). In this study, the grading rubric was expanded to more accurately describe the condition of the CMPs. The survey was expanded to encompass 819 surveyed pipes across Kansas. The goal of the study was to collect data using a large number of CMP field observations, and to make inferences on CMP performance without damaging the pipe by sawing out samples. Using the large population of observational data, Stratton et al. (1990) determined that a 1975 pipe policy change resulted in CMPs that were drastically underperforming before their service lives. Using the findings of the Stratton et al. study, a new state policy was developed in 1991, which restricted the use of galvanized CMP to only certain construction situations and increased the minimum gage thickness of all new CMP used in the field.

In 1993 KDOT updated to a new pipe policy, which favored the use of aluminum coated (aluminized) CMP in the field. Due to the changes in gauge thickness requirements and changes in the protective coating alloy, a new CMP survey is necessary in order to understand the effectiveness of these policy changes, and to investigate further corrosion mitigation solutions.

A survey of observed CMP conditions was conducted for 80 sites across KDOT districts one and four. Along with observational data, field resistivity measurements were taken at each location. The observational data was surveyed in the same manner as Stratton et al. (1990). Visual inspection of the crown, side, exterior, and invert, along with a general rating of the CMP condition were recorded. A small description was also included for CMPs with excessive silting, exterior non-corrosion induced damage, or disjointed seems. General conclusions were made on the deterioration and general condition of CMPs using the field observations.

Several state DOTs and transportation boards have presented unique methods to predict CMP deterioration using field conditions (Beaton & Stratfull, 1962; CALTRANS, 1999; Cerlanek & Powers, 1993). Field resistivity and pH measurements have been widely used to determine corrosion potential at project sites. One of the most widely used methods of estimating the service life of CMP is the California Test 643 (CALTRANS, 1999). The California Test 643 empirically predicts the years until a CMP perforates based on the resistivity and pH of samples taken in the field. However, methods relying on pH and resistivity may not accurately predict conditions in the field as the pH of top soil fluctuates throughout the year and soil resistivity measurements rely on varying testing conditions (e.g. degree of compaction, saturation, etc.). Field data collected by Stratton et al. (1990) were compared to the data collected in this study to estimate the true deterioration rates of CMPs between the two surveys. Results from this prompted an additional laboratory study to determine a reliable method of better predicting the deterioration of CMPs in the field. A laboratory leachate testing method was developed to recreate soil-water interactions that happen in the field.

The laboratory testing included an initial test of the anion composition, resistivity, hydrogen ion composition (pH), and biological activity of a 1:1 soil-water slurry. A timed leachate test was created to recreate CMP conditions in the field. In the field, CMP inverts are exposed to leachate water that has been exposed to topsoil just before coming into contact with the CMP. To recreate these conditions in the laboratory, a soil sample was immersed in deionized water and left to soak for 24 hours. A sample of the leachate slurry was collected and the sample was rinsed. This process was repeated to have a 24, 48, and 72-hour sample distribution. The goal of the timed leachate testing was to determine how pH, resistivity, and ion mobilization change as soil is continuously saturated.

The main objectives of this study were to survey the conditions of CMPs in KDOT districts one and four and form conclusions based on comparing data collected in this survey to historical data using the Stratton et al. (1990) method of visual inspection. An additional objective compared the accuracy of current service life prediction methods with conditions observed in the field, to develop a laboratory method for better predicting the deterioration of CMPs in the field.

Following the introduction, the literature review will cover the basic electrochemical principles that govern corrosion and briefly examine the current state of policy, and the practice of estimating the service life of CMPs in the field. After the literature review, a chapter is dedicated to explaining the field and laboratory methodology used in this study. Following the methodology chapter, a chapter is dedicated to explaining the results of this study. The final chapter contains the conclusions of the study and recommendations of future work.

Chapter 2 - Literature Review

This chapter includes a review of the electrochemical theories and concepts associated with the corrosion process. Additional information provided in this literature review include a summary of the different factors that are known to contribute to the corrosion process of buried structures, a review of the materials used for CMP, and the corrosion mechanisms associated with the breakdown of material. This chapter concludes with a review of past studies analyzing the deterioration of CMPs in the field, and how these studies influenced policy and the methods used to determine the service life of CMPs in the field.

2.1 Corrosion

All metals, except noble metals (e.g. gold, silver, and platinum), exist in a natural state as compounds in the form of oxides, hydroxides, carbonates and silicates. To separate metals from natural ores large amounts of energy are supplied during extraction, thus entropy is reduced making the product unstable. The process of corrosion has been described as extractive metallurgy in reverse (Cicek, 2014). The energy introduced to the system quantified as a change in Gibbs free energy as shown in Figure 2-1. Metals in the elemental form are thermodynamically less stable than in their compound form. This makes the corrosion process spontaneous.

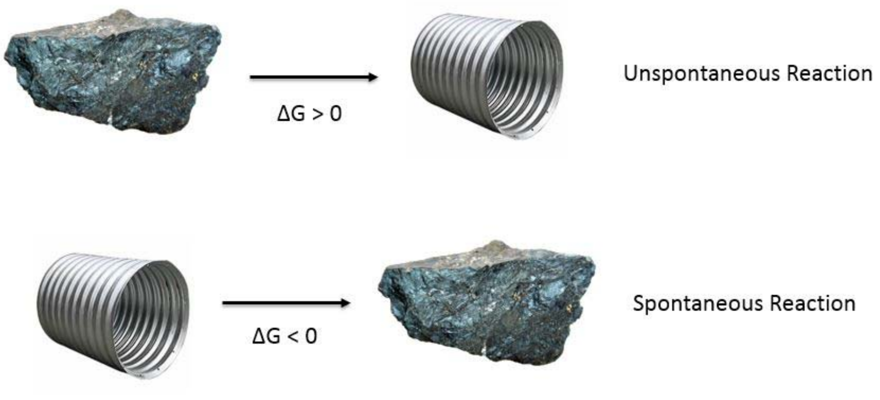

Figure 2-1: The Change in Gibbs Free Energy Associated with Extractive Metallurgy

An anode, cathode, electric pathway, and an electrolytic pathway are required to induce the electrochemical process of corrosion. The anode, or the location of metal dissolution, acts as a reducing agent by generating electrons that travel to the cathode via an electrical pathway. The cathode simultaneously produces positively charged ions, which travel back to the anode through the electrolytic pathway, thus functioning as an electrical circuit (Cicek, 2014).

The dissolution of iron to brown-red rust is an example of the corrosion process. First, an anodic half reaction iron (Fe) is oxidized producing free electrons (e^-).

$$2 \times (Fe \rightarrow Fe^{2+} + 2e^-) \qquad (2.1)$$

The electrons travel via electrical pathway reducing the water (H_2O) and free oxygen (O_2) in a cathodic half reaction.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (2.2)$$

These half reactions make up the oxidation-reduction reaction producing iron (II) hydroxide ($Fe(OH)_2$) which is further oxidized to produce iron (III) oxide (Fe_2O_3), or brown rust. The dissolution of iron results in material loss due to the production of water-soluble iron (III) oxide. Deposits of iron (III) oxide form on the surface and are observed as rust, as shown in Figure 2-2

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \qquad (2.3)$$

$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 \cdot H_2O + 2H_2O \qquad (2.4)$$

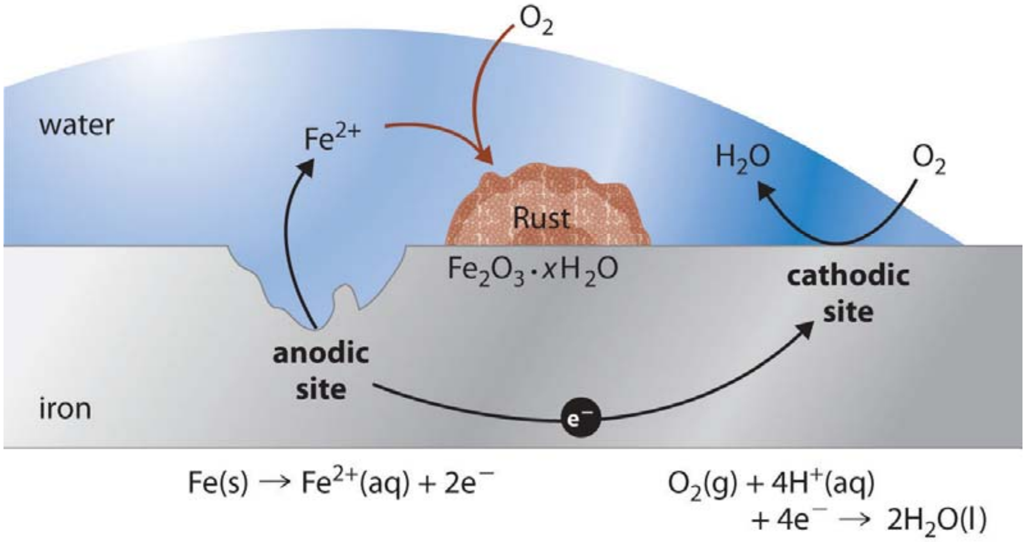

Figure 2-2: Illustrating the Oxidation of Iron (Averill & Eldredge, 2012)

The electrons generated in the corrosion reaction move from the anode to cathode due to the difference in potential energy of electrons at the cathode and anode (Kotz et al., 2015). This is known as the electromotive force, or electrochemical potential. The electrochemical potential (E) is derived chemically using the Nernst Equation,

$$E = E° - \left(\frac{RT}{nF}\right) \ln Q \qquad (2.5)$$

where, R is the universal gas constant (8.314 J/K-mol), T is the temperature in Kelvin, F the Faraday constant (9.648×10^4 C/mol), n is the number of moles of electrons transferred between oxidizing and reducing agents, and $E°$ is the electrochemical potential under standard conditions. The electrochemical potential of a reaction is found by comparing the known standard reduction potentials of anodic and cathodic half reactions such that

$$E° = E°_{cathode} - E°_{anode} \qquad (2.6)$$

The reaction quotient, Q, is

$$Q = \frac{[C]^c[D]^d}{[A]^a[B]^b} \qquad (2.7)$$

$$aA + bB \rightleftharpoons cC + dD \quad (2.8)$$

where, A,B,C,D are product-reactant concentrations and a,b,c,d are stoichiometric coefficients.

A correlation between the electrochemical potential (electromotive force) and current density using Ohms law is made by modeling the electrochemical reaction as a simple circuit as shown in Figure 2-3.

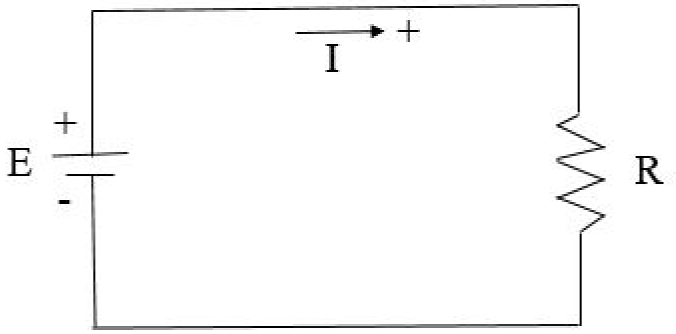

Figure 2-3: Simple Circuit

The current density, i, is represented as

$$i = \frac{E}{RA} \qquad (2.9)$$

where, E is the electrochemical potential, R is the resistance to current, and A the cross-sectional area of material. The principles of Faraday's law relate the current density (i) of the electrochemical reaction to the theoretical mass loss rate of anodic material. The corrosion mass loss rate of material (MR) is

$$MR = K \cdot i \cdot EW \qquad (2.10)$$

where, K is 8.954×10^{-3} g cm^2/μA m^{2}d. The dimensionless equivalent weight, EW, is

$$EW = \frac{W}{n} \qquad (2.11)$$

where, W is the atomic weight of the metal being oxidized and n is the number of electrons needed to oxidize the reaction (ASTM, 2015).

Preferential galvanic corrosion is widely used to mitigate corrosion. By coupling metals or alloys with a more anodic metal or alloy, the corrosion of the cathodic metal of greater nobility is generally reduced (Revie, 2011). The severity of galvanic corrosion depends on the difference in electrochemical potential, which is illustrated as the order of metals and alloys on the galvanic series (Cicek, 2014). The galvanic series is a comparison of metal nobility as shown in Figure 2-4.

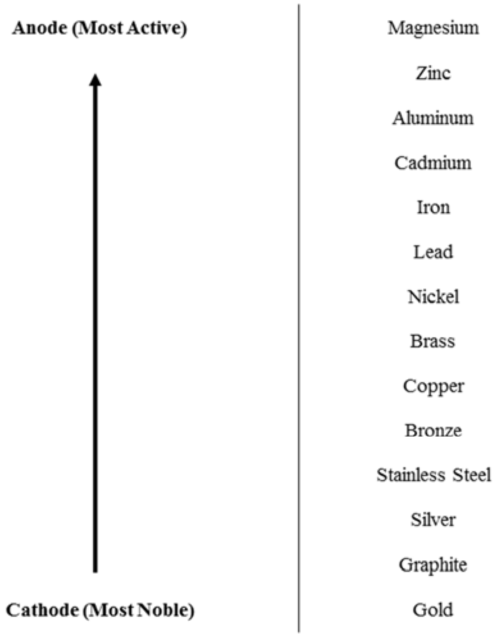

Figure 2-4: Galvanic Series

Revie (2011) used 38.1 mm (1.5 inch) discs, 1.6 mm (1/16 inches) thick, composed of material A and material B clamped together so that only the edges were exposed to illustrate preferential galvanic corrosion. The weight loss of material A was measured after seven years of being exposed to a marine environment. The weight loss associated with iron coupled with zinc was shown to be more than three times less than iron coupled with iron, as shown in Table 2-1. This phenomenon of preferential galvanic corrosion is widely used by industry to protect metals and alloys from corrosion. By providing, a surface layer of a more anodic material the underlying metal gains added protection from corrosion. The anodic surface acts as a sacrificial layer, even providing protection in locations where discontinuities occur in the coating (Revie, 2011).

Table 2-1: Corrosion of Galvanic Couples in Different Atmospheres after Seven Years of Exposure (Revie, 2011)

Couple (Material A/Material B*)*	Weight Loss (milligrams)
Zinc/Zinc	195
Zinc/Iron	349
Iron/Iron	470
Iron/Zinc	147

Material passivity is another important aspect when considering corrosive deterioration. Passivity is the process in which a metal or alloy exhibits a much higher corrosion resistance than its electrochemical potential would indicate (Cicek, 2014). Figure 2-5 details how an ideal passive metal would react to electrochemical potential. As the electrochemical potential of an anode increases so does the current density, which correlates to an increased corrosion rate. The anode actively corrodes until the critical current density (i_c) is reached. A passive film is formed at the passivation potential (E_p) at which point the current density drops to a passive current density (i_p), thus a decreased rate of corrosion.

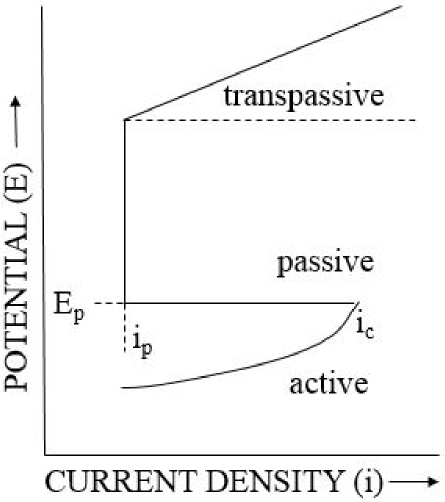

Figure 2-5: Idealized Anodic Polarization Curve for a Passive Metal (Revie, 2011)

All metal and alloys form a thin protective corrosion product on the surface as a result from reacting with the environment. Notable exceptions are noble metals such as gold that exist in nature in an unreactive elemental state. Some of these films have special characteristics that enable them to provide superior corrosion resistant surfaces. The passive films that develop are critical in controlling the corrosion process by preventing the spontaneous reaction of reverting metals to ores (Revie, 2011). Conditions for which passivity occurs are illustrated in Pourbaix diagrams. Pourbaix diagrams graphically represent electrochemical equilibria of metals in different aqueous solutions based on pH and electrochemical potential. Pourbaix diagrams are used to establish theoretical domains of passivity, immunity and corrosion. Figure 2-6 is a simplified Pourbaix diagram of iron in water.

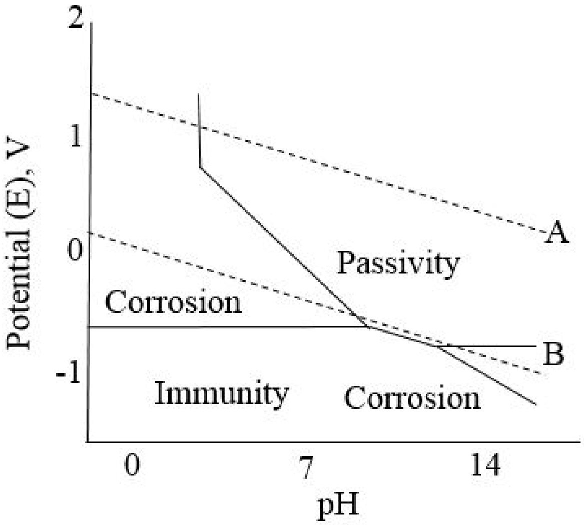

Figure 2-6: Simplified Pourbaix Diagram for Iron-Water (Pourbaix, 1963)

The dashed line A in Figure 2-6 represents the reversible oxygen line and dashed line B represents the reversible hydrogen line. Water is thermodynamically stable between dashed lines A and B. Outside of these boundaries water either decomposes to form hydrogen gas (H_2), or is oxidized to form oxygen gas (O_2). Only the region between the reversible oxygen line and reversible hydrogen line is considered when analyzing the corrosion and passivity of a metal or alloy in water (Kelly et al., 2003). This simplified Pourbaix diagram outlines the importance of pH and potential energy when considering an electrochemical reaction. Generally, a corrosive reaction is achieved when the pH is low and the potential energy is high, while a metal is usaully rendered passive in a high pH environment with low potential energy.

2.2 Contributing Factors of CMP Corrosion

Temperature, humidity level, hydrogen ion concentration (pH), concentrations of dissolved oxygen, nature of electrolyte, presence of aggressive ions, flow rate, and metal impurities all are factors that specifically contribute to CMP corrosion (Cole & Marney, 2011).

2.2.1 Resistivity

Resistivity is a material property that quantifies the ability of a given material to resist the flow of current. Resistivity(ρ) is defined as,

$$\rho = \frac{RA}{L} \qquad (2.12)$$

where, R is the resistance (Ohm), A is the area (m^2), and L is the length of material (m). Resistivity is a fundamental material property, whereas resistance depends on the shape and size of specimen as shown in Figure 2-7. The greater the resistivity for a material, the less capable the material is at providing an electrical pathway for an electrochemical corrosion reaction. Thus the greater the resistivity of a material, the lower the corrosion potential (ASTM, 2015)

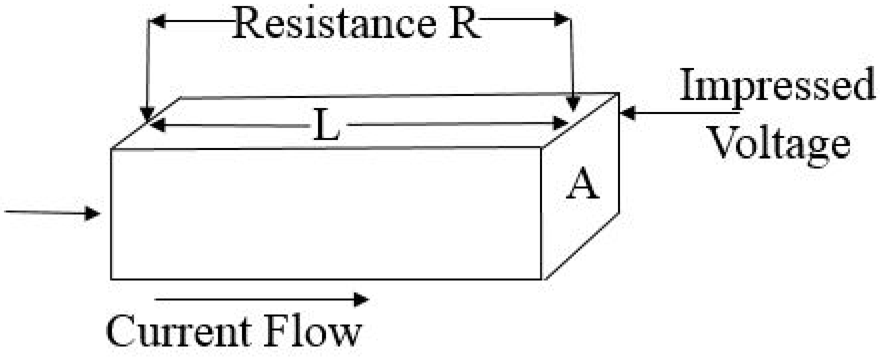

Figure 2-7: Resistance Diagram (Chaker, 1981)

Soil resistivity is known to be primarily affected by pore fluid, salinity of the pore fluid, temperature, moisture content, porosity, and presence of inert material, such as stones and gravel (AASHTO, 2007). Typical resistivity values associated with soil and rock is shown in Table 2-2.

Table 2-2: Resistivity of Common Geological Materials (Elias et al., 2009)

Geomaterial	Resistivity (Ohm-m)
Clay	1 - 20
Sand, wet to moist	20 - 200
Shale	1 - 500
Porous Limestone	100 - 10^3
Dense Limestone	10^3 - 10^6
Metamorphic Rocks	50 - 10^6
Igneous Rocks	10^2 - 10^6

In shallow surfaces, the most important geological factor that controls bulk electrical resistivity is the spatial distribution of pore-fluid electrolytes (Everett, 2013). This is due to most soils being electrolytic, with pore fluid ions carrying the charge throughout the volume of soil (which includes air, pore fluid, and soil particles) (Figure 2-8), with the exception being clay soils. Because of the polarizing nature of clay minerals, the soil matrix is what controls the flow of current. Figure 2-9 compares the resistivity of the solid soil matrix to the resistivity of pore water electrolyte for clays and sands. Salinity is the measurement of the amount of soluble ionic salts in water. The greater the salinity of the pore water fluid, the greater amount of dissociated ions able to carry an electric current, thus a lesser resistivity. The major dissolved anions in soil pore fluid electrolytes are chloride, sulfate, phosphate and bicarbonate, with chloride and sulfate the most active anionic constituents in the corrosion process (Elias et al, 2009).

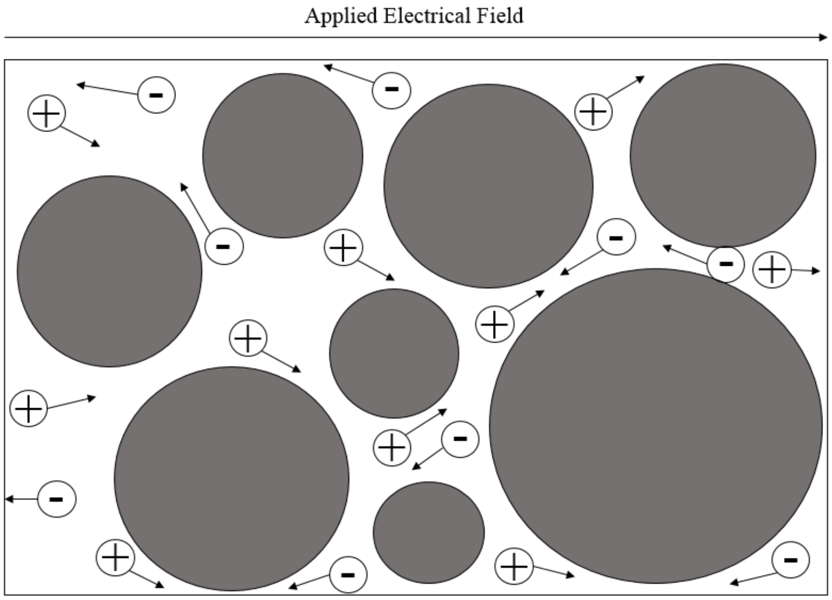

Figure 2-8: Polarization of Pore Fluid Electrolytes

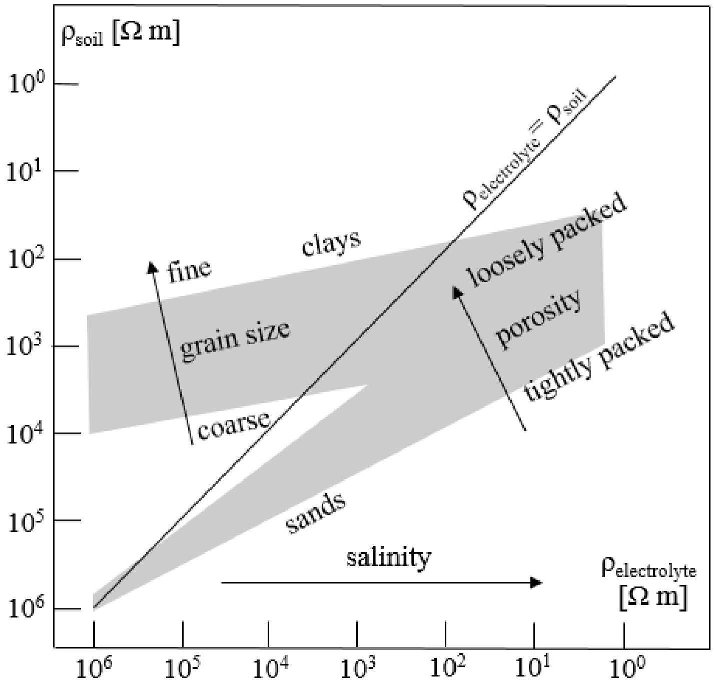

Figure 2-9: Electrical Conductivity of Saturated Soils, after Santamarina et al. (2005)

Chloride salts are a known strong electrolyte, which completely dissociates itself to charge carrying ions. Unlike coastal regions where atmospheric chloride deposition is high, Kansas' potential sources of chloride result from man-made applications. Fertilizers such as muriate of potash (KCl), ammonium chloride (NH4Cl), calcium chloride (CaCl2), magnesium chloride (MgCl2), and sodium chloride (NaCl) are all used in agriculture, with some fertilizers containing up to 74% chlorine (Kansas State University Department of Agronomy Extension, 2016). Another source of chloride in soil pore fluid is from the leaching of sodium chloride (NaCl) from roadway deicers. On average, 82,000 T of roadway salt is used in the state of Kansas to prevent snow and ice from binding to the roadway (Kansas Department of Transportation, 2016b).

Sulfate pockets in soil can be both naturally occurring, and the result of man-made activity. Along with providing an electrolytic medium for current, sulfates may combine with free oxygen to form sulfuric acid that can lower pH at high concentrations. The most notable occurrence of sulfate is from mining waste deposits (AASHTO, 2007). In areas of humid climate, such as the eastern parts of Kansas considered in this study, the risk off acidic soil is greater due to the leaching of alkaline salts leached through century's time, leaving the resulting soil in an acidic state (AASHTO, 2007).

The Ohio Department of Transportation conducted a comprehensive field study in 1982 to investigate the relationship between resistivity and pH of soil and water samples taken in the CMP's invert with corrosion potential in the field, of 1,616 CMPs including galvanized steel CMPs and reinforced concrete (Meacham et al., 1982). Results of soil and water sampling were compared with land use and geological data to make inferences of how the states mining industry and peat rich deposits influence the corrosion potential of the soil. Meacham et al. found that water pH measurements were generally more acidic in areas where mining had occurred. Chemical testing of water taken from the CMP’s invert indicated that in areas of low pH, high pyrite coal was present evident by the existence of iron and sulfate ions in the water sample. Although land use patterns and soil characteristics such as ion concentration were considered, the only parameters that indicated a significant effect on CMP durability was water pH and abrasion potential.

2.2.2 Hydrogen Potential

Hydrogen Ion Concentration (pH) is also widely used to determine the risk a certain area poses in facilitating aggressive corrosion. The electrochemical corrosion process is largely dependent on the pH of the medium (Cicek, 2014). The medium is the pore water fluid in contact with the corrosion surface for underground soil corrosion. The effect of pH on the corrosion process can be demonstrated by a Pourbaix diagram illustrating how the pH can change the chemical equilibria for a given material, as is the case for aluminized CMPs that have a layer of aluminum coating on the surface. As the pH diverges from neutral, soluble products such as Al3+ and Al2O3 are formed allowing for the corrosion of the underlying metal. At pH ranges of approximately 3.5 to 8.5 the reaction is referred to as passive, meaning a protective aluminum oxide coating is produced further strengthening the metal’s resiliency to corrosion. Most passive films that form on the metal surface, such as aluminum oxide Al2O3, are considered amphoteric oxides. The pH of soil pore fluid not only determines the product at equilibria but contributes to the breakdown of passive films. An amphoteric oxide will react with either acid or base medium to produce a water-soluble salt, as shown in the breakdown of aluminum oxide in acidic solution,

$$Al_2O_3 + 6H_3O^+ \rightarrow 2Al^{3+} + 9H_2O \quad (2.13)$$

where, the hydronium ion $H_3O^+$is representative of the protonation of aqueous water, and the aluminum ion Al^+ is as a Bronsted acid being readily soluble in water. Aluminum oxide is also known to breakdown in basic solutions such as

$$Al_2O_3 + 2OH^- \rightarrow 2AlO_2^{\ -} + H_2O \qquad (2.14)$$

where the free hydroxide OH^- reacts with aluminum oxide forming the soluble anion $AlO_2^{\ -}$. The amphoteric phenomena described in Equations 2.13 and 2.14 is shown as a Pourbaix diagram in Figure 2-10. The theoretical breakdown of aluminum oxide film occurs as the pH diverges from neutral (7) to approximately 4 and 8.5. Environments that experience acidic or basic runoff beyond these limits, such as those found near some agricultural or industrial sites, may render the aluminum coating useless by not allowing the formation of passive films.

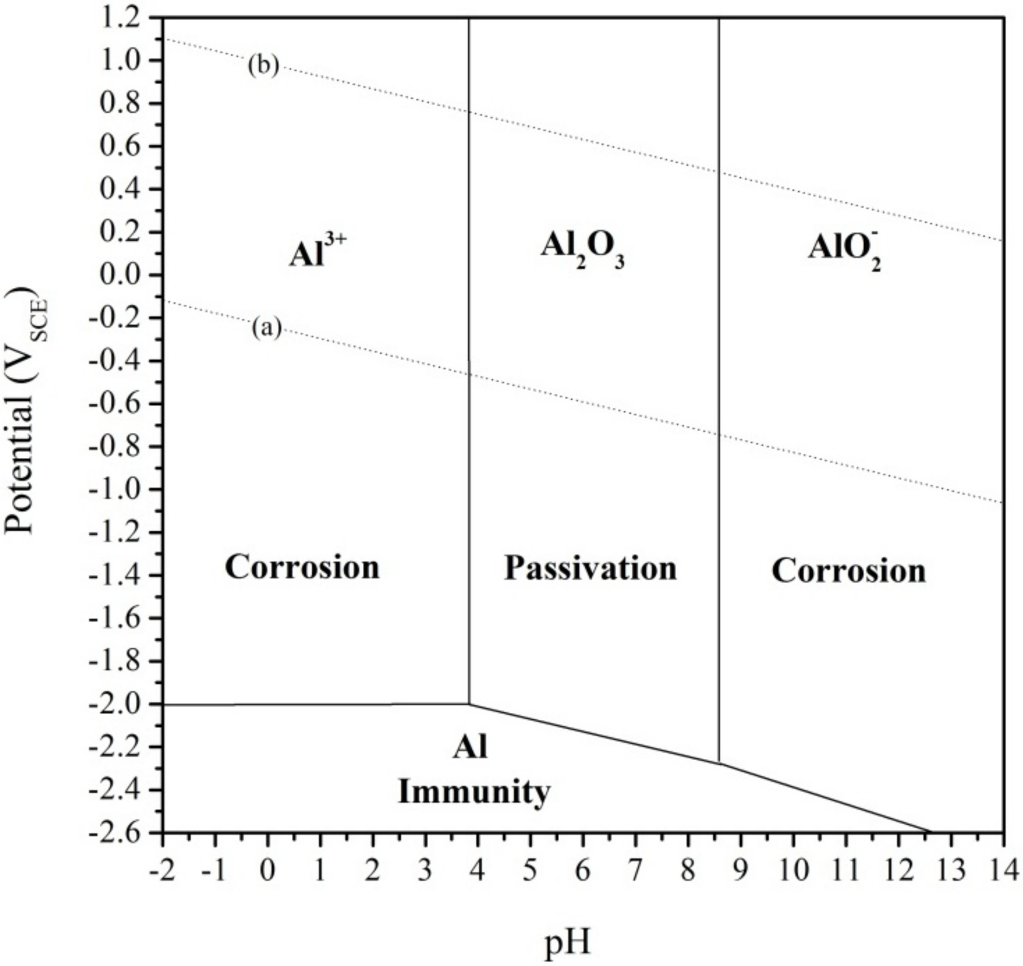

Figure 2-10: Pourbaix Diagram of Pure Aluminum in 25° C Aqueous Solution (Sukiman, et al., 2012).

Zinc is widely used as a protective surface layer due to its galvanic preferential corrosion characteristics. Figure 2-11 shows the boundaries for which zinc displays passivity. The product zinc oxide (ZnO) does not show passivity in itself due to its porous structure, but further reacts due to atmospheric weathering to produce zinc carbonate film $ZnCO_3$. As shown in Figure 2-11, zinc corrosion occurs as the pH diverges from neutral to 6 and 10.5. Theoretically, zinc films breakdown much more readily than aluminum films in an acidic medium. It is generally considered that measured soil or water pH between 5.5 and 8.5 are not severely detrimental to culvert life (AASHTO, 2007).

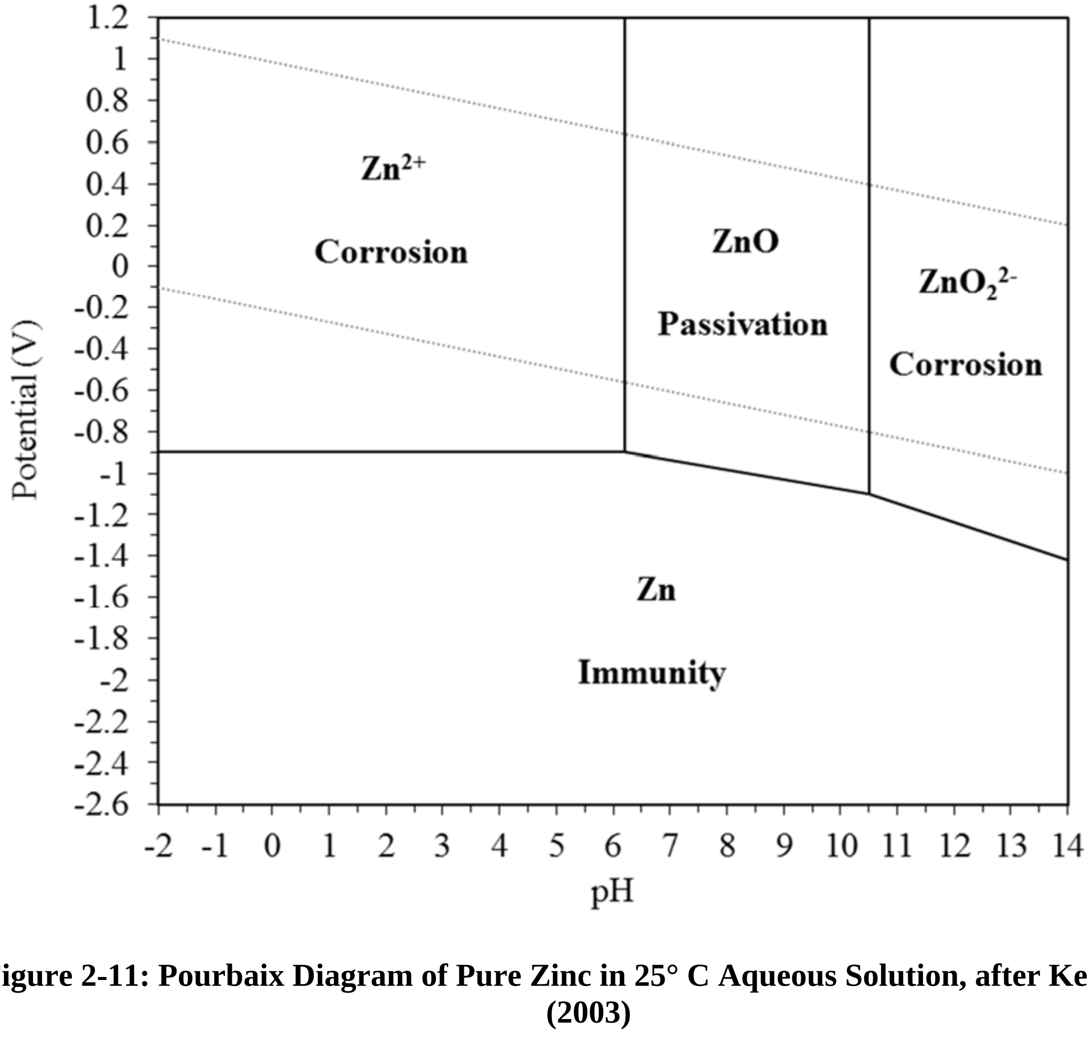

Figure 2-11: Pourbaix Diagram of Pure Zinc in 25° C Aqueous Solution, after Kelly et al. (2003)

2.2.3 Flow Velocities and Abrasion

High flow velocities and turbulences inside a CMP expedite the corrosion process by removing the passive films, exposing underlying metal. Flow rates have been widely associated with the deterioration of CMPs through the process of abrasion. Abrasion is the wearing of the CMP surface due to the shearing of suspended materials flowing through the CMP, usually occurring in the invert. Flow velocities in excess of 4.5 m/s (15 ft/s) carrying a bed load (suspended materials) are considered very abrasive (AASHTO, 2007).

2.4 Durability of CMPs in Kansas

A previous study conducted under the Bureau of Materials and Research determined the performance of galvanized CMPs throughout Kansas (Stratton, 1989). The study took observations from KDOT projects located in 10 different counties representing all six KDOT districts (Figure 2-12). The objective of this study was to evaluate the performance of galvanized CMPs installed since 1977. A rating system shown in Table 2-3 was created to quantify the visual inspection of the CMPs.

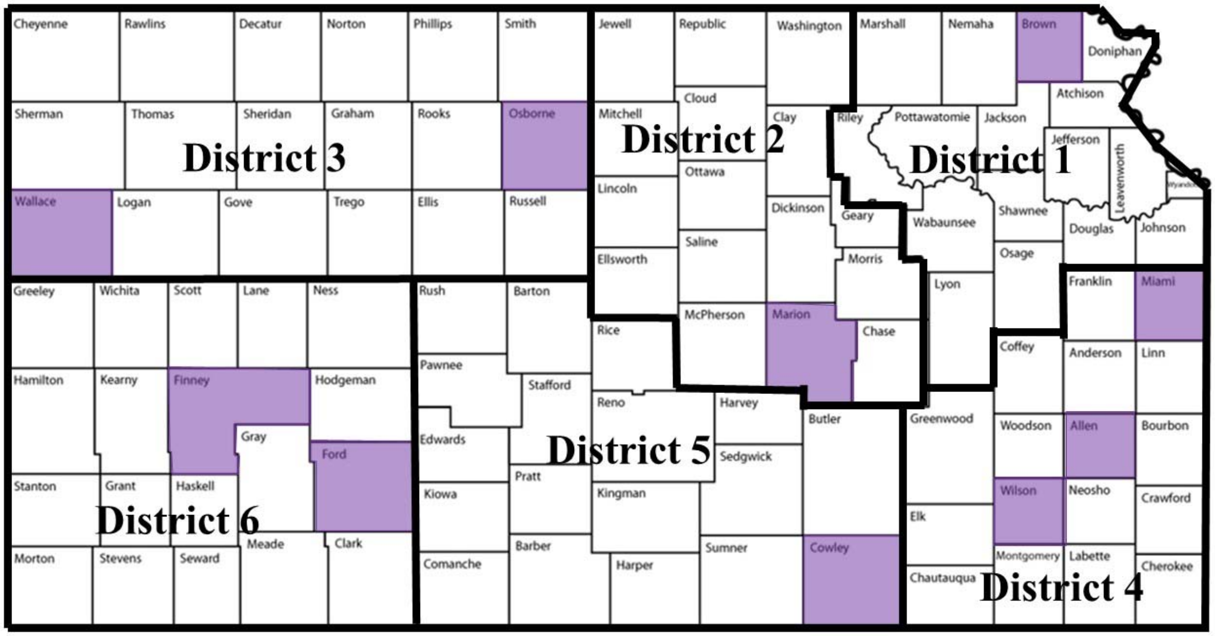

Figure 2-12: KDOT Districts

Table 2-3: 1989 Report Rating System (Stratton, 1989)

1	CMP in excellent condition.
1+	CMP in excellent condition. Minor inlet or outlet damage or erosion. Light silt and/or oxidation.
2	CMP in good shape. Heavy oxide film. 0-40% silting and/or minor to moderate inlet or outlet damage.
2+	CMP in reasonably good shape. Heavy oxide film. May have 40-50%silting. May have moderate to heavy inlet &/or outlet damage. Minor settling or distortion.
3	CMP rusting. No distortion or settling. May have silting.
3+	CMP rusting. Distortion &/or settling. May have silting.
4	CMP heavily rusted with distortion and/or settling. May have silting.
5	CMP failed. Because of distortion, collapse, rusting, or complete silting.

Figure 2-13 shows a CPM inspected using the Stratton (1989) rating system shown in Table 2-3. Four locations of the CMPs were rated using this system: the invert (bottom), the interior side, the interior crown or top, and the soil side exterior. The CMP shown in Figure 2-13 was given a rating of 1+.

Figure 2-13: Example of a CMP with a 1+ Rating (Stratton, 1989)

Data including the thickness of zinc coating, and overall CMP thickness were recorded in the Stratton study. In total 103 galvanized corrugated metal CMPs were observed. No invert rusting due to water was found west of Osbourne County and the worst performing CMPs were located in districts one and four. It was also observed that silting had become a major problem in CMPs throughout the state. Silting is the buildup of sediment in the invert of the CMP, which contributes to the loss of overall flow capacity. Silting may contribute to hidden corrosion from trapped moisture remaining in contact with the CMP. Standing water or the presence of silt was estimated to be the primary cause of damage for one-half of the heavily rusted CMPs. Proper design and maintenance were cited as principal means of mitigating the detrimental effects of silting. Stratton (1989) concluded that within the next ten to fifteen years, over 50% of the CMPs examined would be perforated due to rust, which may lead to structural collapse. Along with silting, it was suggested that an abundance of agriculture chemicals used in areas adjacent to CMP locations contributed to an accelerated deterioration by etching away the zing coating.

The results from Stratton (1989) indicated that galvanized CMPs installed since 1977 were failing at a much faster rate than the anticipated design life due to KDOT policy, which prompted an additional study performed by Stratton et al. (1990). This study was expanded to include 819 CMPs surveyed via visual inspection. A new rating system was designed to better represent CMP conditions by including a larger range of numerical ratings as shown in Table 2-4.

Table 2-4: 1990 Report Rating System (Stratton et al. 1990)

95-90	Spelter like new to very dull
87.5	Pinpoint rest
85.0	Spelter gone
80.0	Light rust film
70.0	Shallow pitting
60.0	Scaley rust or pits not halfway through metal
45.0	Heavy rust or pits halfway through metal
30.0	Heavy rust or pits 3 through metal
15.0	Heavy rust or holes through metal
0.0	Large areas of metal gone

Observations of side, crown, exterior and invert were recorded along with the CMP diameter, hydraulic adequacy, backfill material, watershed description, alignment, slope, and joint condition where applicable. From the field of 819 CMPs, 86 CMPs were selected for further testing. A 38mm (1.5 inches) diameter sample was taken with a hole saw along with field measurements of pH and resistivity of the backfill soil. The CMP samples were used to measure wall thickness and zinc coating by means of a micro test gauge.

Stratton et al. (1990) determined that KDOT districts one and four exhibited the most rapid deterioration, while CMPs in districts three and six exhibited much longer service life. By extrapolating the trend lines for CMPs installed prior to, and since, 1975 it was determined that CMPs installed after 1975 were deteriorating at rate substantially faster. This supported the findings of the first KDOT study (Stratton, 1989). Reasons for rapid deterioration included a policy change in 1975 allowing a lighter gauge and deeper corrugation. A lighter gage meant CMPs would have a smaller amount of zinc sacrificial coating and larger depth for water to pond, and silt to settle. In 1978, helical welded CMPs were approved for KDOT projects, which may have also been a factor in the accelerated deterioration. The weld area was not galvanized the surrounding zinc was relied upon to protect the exposed seem through preferential corrosion. If the preferential corrosion of zinc did not occur, the exposed weld material was prime for corrosion.

Stratton et al. (1990) concluded that changes in construction of CMPs beginning in 1975 played a major role in contributing to accelerated CMP damage due to corrosion. Using the California test 643 with the measurements of soil pH and resistivity, it was determined that most CMPs in the study would have more than 25 years of remaining life based on steel thickness of invert. Stratton et al. (1990) noted that service life predictions are very site specific with readings of pH not always reflecting conditions in the field. Finally, the report concluded that on average CMPs had performed well over the previous 50 years, but site conditions and material properties must be carefully considered in future projects, if an adequate service life is to be achieved.

In 1952 and 1953, the Kansas Highway Commission installed four experimental aluminized CMPs in connection with galvanized CMPs. Three of these were inspected during the spring of 1999. Inspections included taking soil and water pH if applicable, and providing any observations of the condition of the CMPs. Two of the three CMPs inspected observed that minimal deterioration of the aluminum coating had occurred whereas the galvanized portions had heavy invert rusting with the galvanized coating etched away. Noticeable rusting had also occurred on the soil side of one of the galvanized CMPs. Table 2-5 shows the results of soil and water pH and resistivity measurements taken in the field at the time of installation along with the estimated service life of the CMP according to the California method.

Table 2-5 KDOT Aluminized CMP Test Sites

Location	Gage	Soil pH	Soil Resistivity	Water pH	Water Resistivity	Service Life Estimation (CALTRANS, 1999)
Dickinson	12	-	919	7.8	763	49.2
Decatur	12	7.5	4405	-	-	100.9
Pratt	14	7.5	3735	7.1	2940	41.1

2.5 Review of CMP Studies Conducted by State and Federal Agencies

Both the Florida Department of Transportation and CALTRANS have conducted similar studies as KDOT regarding service life of cross road drainage structures, specifically regarding corrosion. Ohio, Arkansas, Missouri, and Minnesota Departments of Transportation sponsored similar studies to determine how different CMP materials interact with corrosive agents within the environment and determine the performance of CMPs (Taylor & Marr, 2012; Missouri Department of Transportation, 2000; Meacham et al., 1982; Boyd et al., 2004). The objective of these studies was to find a material that can reliably maintain the desired hydraulic and structural capacity needed for highway infrastructure over a set design life. Each study considered soil and water properties with varied success as described below.

Missouri, which shares the same humid climate as the eastern half of Kansas, has conducted various studies since the 1930s to monitor and evaluate the performance of different CMP materials used in construction (Missouri Department of Transportation, 2000). For example, MoDOT attempted to determine the life expectancy of galvanized steel CMP by performing field and laboratory testing on 153 CMP. The results of the study indicated that the CMPs would need to be replaced due to deterioration after approximately 44 years after installation. The study neglected the influence of soil parameters (e.g. moisture content, pH, chloride content, sulfide content, total hardness) for the CMP's deterioration. After years of monitoring CMP performance, the Missouri Department of Transportation also concluded that aluminized CMPs showed evidence of having a longer life expectancy than galvanized CMPs in similar environments (Missouri Department of Transportation, 2000).

The Arkansas State Highway and Transportation Department compared the durability of different CMP materials with water pH, soil resistivity, soil potential, and CMP age (Boyd et al., 1999). The study included 19 galvanized and two aluminized CMPs. It was found that galvanized CMP performed well under "dry stream" conditions but when the invert was continuously exposed to aqueous corrosion, deterioration was massively accelerated. The two aluminized CMP sites were observed to be in fair condition, with one site being installed in connection with a galvanized CMP. The aluminized section was observed to be in good condition being only slightly discolored, while the galvanized section showed evidence of the beginnings of corrosion damage. Other than, the physical deterioration reported no statistically significant measurable soil/water properties were identified to predict corrosion potential.

More recently, the Minnesota Department of Transportation sponsored a study where the Natural Resources Conservation Service Web Soil Survey was utilized to gather pH and soil resistivity data to predict the service life of steel CMPs via the California Method (CALTRANS, 1999). Taylor and Marr (2012) postulated that collecting soil and water samples throughout the state was not practical and assumed that water pH and soil resistivity collected in the invert was greatly affected by adjacent soil characteristics. Therefore, they used online soil type information to identify areas at risk for increased corrosion potential. By comparing the Web Soil Survey (NRCS Soil Survey Staff, n.d.) pH to the known pH of specific locations in Minnesota, it was determined, that the Web Soil Survey on average estimates a lower pH and consequently a conservative service life estimation. It was concluded that a further study should be developed to map the projected service life for steel CMPs based on available geographic soil characteristic data.

At the national level, the Ocean City Research Corporation investigated 32 CMPs, 21 of which were Aluminized Type 2 (Ault & Ellor, 2000). The sites were selected from three different field investigations representing different areas of the country. Ten CMPs from Santiam Highway located in Oregon, 6 CMPs from the Natchez Trace Parkway in Alabama, and 5 CMPs in Maine were selected for the study. By using a Mitutoyo micrometer, the depth of the deepest pit of the invert was compared to the initial manufactured thickness yielding the percent perforation shown in Table 2-6.

Table 2-6: Summary of Field Data on Aluminized Type 2 CMPs (Ault & Ellor, 2000)

Culvert Location	Thickness - Inches		Percent Perforation	Soil		Resistivity		Calif. Pred. Life	Actual Age	
	Crown	Invert		pH	Resistivity	pH	Resistivity		Years	Percent of Calif.
ME Dexter	0.057	0.011	80.70%	6.7	5138	7.4	7389	30	16	53%
ME Garland	0.072	0.07	2.78%	6.9	8130	6.8	9147	44	10	23%
ME New Gloucester	0.072	0.071	1.39%	5.3	N/A	6.4	7426	38	16	42%
ME Orrington	0.076	0.07	7.89%	6.5	3609	6.9	6186	32	10	31%
ME Ripley	0.098	0.097	1.02%	5.4	5036	6.6	9677	36	16	44%
NT 310.0	0.058	0	100.00%	6.8	4710	7	17241	30	14	47%
NT 310.1	0.056	0	100.00%	5.8	2646	7.1	22556	17	14	82%
NT 310.6 North	0.057	0.054	5.26%	6.8	6148	7.2	5272	32	14	44%
NT 311.9 South	0.056	0.056	0.00%	7.6	1601	7.7	6061	38	14	37%
NT 312.4 East	0.057	0.056	1.75%	7	2594	7.2	2609	29	14	48%
NT 312.4 Single	0.057	0.057	0.00%	7	2882	dry	dry	30	14	47%
SH 100+15	0.058	0.056	3.45%	5.3	3258	7.5	23438	17	14	82%
SH 104+45 East	0.126	0.124	1.59%	5.7	4631	7.2	19608	48	14	29%
SH 104+45 West	0.13	0.129	0.77%	5.7	4631	7.2	19608	48	14	29%
SH 123+76	0.056	0.055	1.79%	5.6	11152	6.6	18868	27	14	52%
SH 13+00	0.057	0.057	0.00%	6.7	3464	6.8	46875	26	14	54%
SH 18+20	0.057	0.054	5.26%	6.5	10352	7.3	18987	32	14	44%
SH 38+12 East	0.073	0.07	4.11%	5.4	2973	6.4	13700	21	14	67%
SH 38+12 West	0.073	0.07	4.11%	5.4	2973	6.4	13700	21	14	67%
SH 44+50	0.057	0.049	14.04%	5.4	4212	7.5	24000	19	14	74%
SH90+38 East	0.057	0.056	1.75%	6.3	3914	7.2	21898	23	14	61%

The percent of perforation was compared to the linear estimation of perforation predicted by the California Method for determining galvanized CMPs in Figure 2-14 and Figure 2-15. It was concluded that in the absence of abrasion, Aluminized Type 2 CMPs may have a service life eight times longer than that of galvanized, and 3.5 longer if water side (invert) corrosion is only considered. This was done by removing three apparent outliers as shown in Figure 2-15, Natchez Trace Parkway sites 310.0 and 310.1, and the site located in Dexter Maine. It was observed that at both Natchez Trace Parkway sites wear and corrosion was predominate on the upstream side of corrugation, which is consistent with abrasive wear. Abrasive wearing was also cited as being the reason for the Dexter, Maine outlier as it was observed to experience high velocity flows with a heavy bedload.

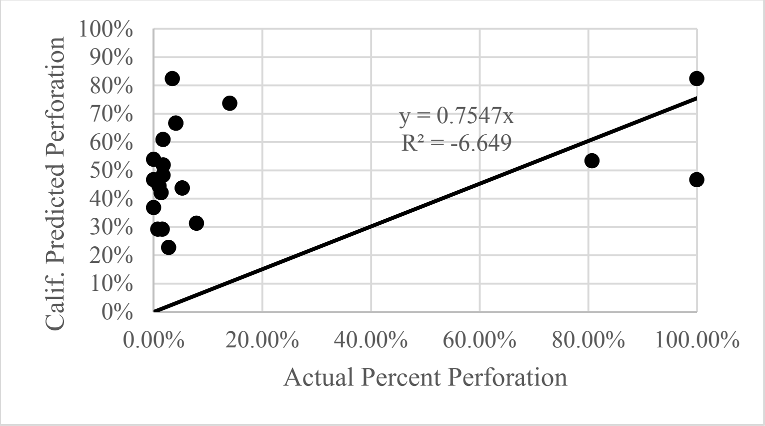

Figure 2-14: California Method curve prediction versus actual percent perforation, all Aluminized Type 2. (Ault & Ellor. 2000)

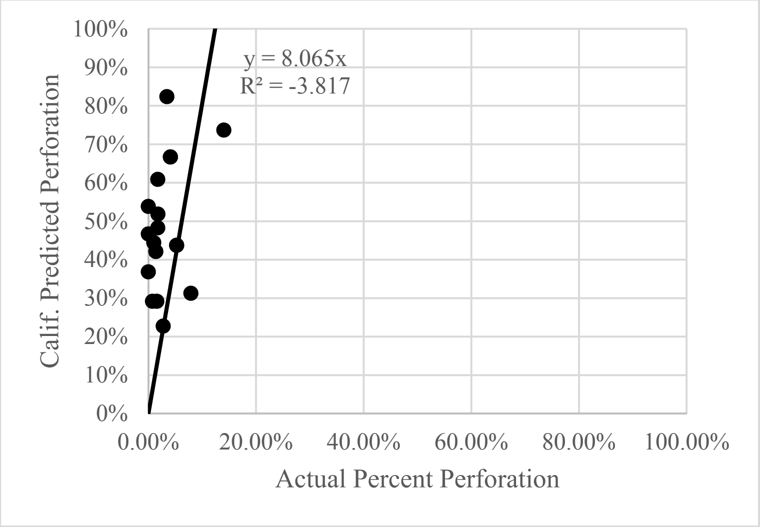

Figure 2-15: California Method curve prediction versus actual percent perforation, all Aluminized Type 2 without outliers. (Ault and Ellor. 2000)

2.5 Service Life Estimation

An alternative method of estimating service life is based on the Florida Department of Transportation's policy. Like the California Method (CALTRANS, 1999) of estimating the service life of galvanized CMPs, the Florida Method uses pH and resistivity measurements collected from soil and water samples to estimate the service life of a 16 gauge (1.63 mm or 0.064 inches) aluminized CMP. As with the California Method, the Florida Method fails to incorporate other site-specific factors that are known to affect the corrosive deterioration of CMP such as frequency of flow, abrasion, organismic activity, silting and standing water. A ±12 years of service life accuracy is used to account for these other factors.

2.6 Current Kansas CMP Policy

The current Kansas CMP policy details guidelines of the appropriate use of different crossroad drainage materials (Kansas Department of Transportation, 2016a). The policy is enforced on any projects where state or federal aid is applied. The policy outlines the acceptable

CMP material by county and if site specific soil and water testing is required. Counties were deemed acceptable for galvanized or aluminized CMP installation based on a comprehensive soil survey conducted by KDOT (Kansas Department of Transportation, 2016a). Currently Cherokee, Crawford and Labette are the only counties were the risk of accelerated corrosion was deemed too high and all use of galvanized and aluminized CMP is prohibited. Many counties that were acceptable for aluminized CMP installation also require resistivity and pH testing at the site of the proposed installation.

In 2001, the Kansas Department of Transportation Bureau of Materials and Research shifted policy allowing for an increased use of aluminized steel CMPs in projects where annual average daily traffic does not exceed 3000 vehicles per day (Kansas Department of Transportation, 2016a). The decision to adopt a policy where aluminized corrugated metal CMPs would be preferred over galvanized arose from several publications highlighting the increased durability of aluminized type 2 CMP material.

Chapter 3 - Methodology

3.1 Field Observations

A field survey was performed to determine CMP deterioration levels and to compare the results with previous studies (Stratton 1989; Stratton et al., 1990). The methodology for surveying each CMP included a visual inspection, general notes on flow conditions in and around the CMP, any observations of structural compromise, location using GPS coordinates, and photographs of the CMP. Visual inspections included assessing the CMP at four different locations: the crown, invert (interior bottom), interior sides, and exterior by using a shovel to remove soil around the exterior. A numerical rating between 0 and 100 was assigned to each of the inspected locations following the KDOT rating system defined by Stratton et al. (1990). The rating system rubric is shown in Table 3-1. The rubric's lowest rating of zero was used for CMPs where large areas of metal were gone due to corrosion, and the efficiency of the CMP to transport water was likely reduced. The highest rating, 100, was reserved for CMPs installed during the year of inspection (2016-2017).

Table 3-1: Grading Description (Stratton et al., 1990)

Rating	Description
95	Spelter like new
92	Spelter dull
90	Spelter very dull
88	Pin-Point rust spots
85	Spelter entirely gone
80	Light rust film
70	Shallow Pitting
60	Scaley rust or pits not 1/2 through metal
45	Heavy rust or pits 1/2 through metal
30	Heavy rust or pits 3/4 through metal
15	Few holes through metal
0	Large areas of metal gone

The goal of the data collection in the field was to find an even spread of existing CMPs representing different ages and locations in districts one and four. Table 3-2 illustrates the population spread using information provided by the KDOT on the installation of metal CMPs throughout Kansas. Note that Table 3-2 does not include all CMPs still in active use, but rather a list of known projects where galvanized or aluminized CMP material was listed in the plans for bidding. CMPs installed before 1989 were located using reference marker and stationing information from Stratton et al. (1990). CMPs installed after 1989 were found by using construction as-built plan sheets from the KDOT ProjectWise database (ProjectWise Explorer V8i (Version 08.11.11.590) [Computer software], 2014) Many attempts to locate older CMPs in the field were unsuccessful due to the resurfacing of highways where older CMPs were likely removed and/or replaced.

Table 3-2: Populations of Recorded CMP Installations

All CMPs (District 1+4)		
Age	**Galvanized**	**Aluminized**
80+	40	0
75-79	35	0
70-74	23	0
65-69	62	0
60-64	54	3
55-59	66	0
50-54	10	0
45-49	4	0
40-44	0	0
35-39	42	0
30-34	11	0
25-29	0	0
20-24	1024	0
15-19	1227	0
10-14	337	12
5-9	0	40

It was observed that heavy silting had occurred in a number of CMPs surveyed (Figure 3-1). Most light silting along the invert could be removed with a shovel and observations of the invert condition were made. In the case of extreme silting or disfigurement of the CMP, readings were not taken. All silting was documented in the general notes of each surveyed CMP. All data collected for each site were recorded using the ARCGIS Collector application, and stored online through the K-State Geographic Information Systems Spatial Analysis Laboratory's online ArcGIS account. Using this application allowed for rapid collection and interpretation of spatial data.

Figure 3-1: CMP with Heavy Invert Silting

3.2 Field Measurements

The California Test 643 recommends the use of a 12 volt single probe system (CALTRANS, 1999). A Collin's Rod, shown in Figure 3-2, was utilized for this field study due to its ability of taking many point measurements with ease. The Collins Rod consists of a 1.016 m (40 inches) long hollow rod with a steel tip separated by a 0.635 cm (0.25 inches) insulating spacer. A wire connects the steel tip, and hollow body to an AC bridge. The rod is then plunged into the soil under investigation, making sure to maintain contact between the tip and soil. The resistivity is read by listening to a speaker connected to the hand held meter and adjusting the resistivity dial until the circuit is balanced, or the sound of the speaker is nullified (Vilda, 2009). The location that the resistivity and soil sample were taken from varied depending on the accessibility of the site and the hardness of the soil/rock.

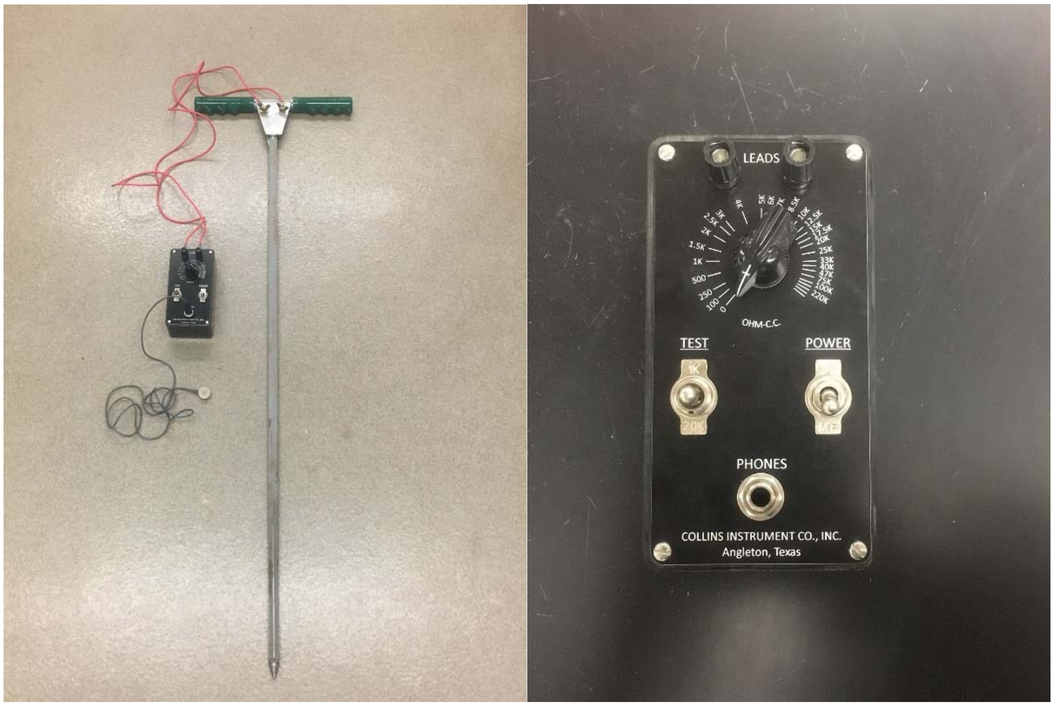

Figure 3-2: Collins Model 54-A Single Rod Soil Apparatus

3.3 Laboratory Testing

The majority of the CMPs with noted deterioration were observed to be in dry conditions. CMPs determined to be under dry conditions did not show signs of standing water in the invert, which could lead to substantial corrosive damage. Soil samples collected from a small sample of CMPs were collected for laboratory testing. The goal of laboratory testing was to determine corrosive agents in the soil, and how they were activated when saturated. The sample size was determined by selecting CMPs that were observed to have varying degrees of deterioration due to corrosion.

A soil sample was collected by removing 5-10 cm of top soil and collecting approximately 300 g of soil in a re-sealable plastic bag. Samples were preserved in a refrigerator immediately after returning from the field to minimize any changes to the chemical or biological characteristics. All samples and measurements were taken within 1m of the invert.

All soil samples were classified using the Unified Soil Classification System (USCS) (ASTM, 2011). Samples were first wet sieved in accordance with ASTM standard C117-17 (ASTM, 2017a). The resulting soil retained on the #200 sieve was subsequently dry sieved in accordance with ASTM standard C136 (ASTM, 2014). To determine the grain size distribution for particles passing the #200 sieve a hydrometer analysis was performed in accordance with ASTM standard D422-63 (ASTM, 2007) for all samples. Atterberg limit tests were conducted for all soils containing fines, and were in accordance with ASTM standard D4318-17 (ASTM, 2017).

Soil pH was determined in the laboratory using the field samples. A 30 g sample was measured and passed through a #8 (2.36 mm) sieve, then added to a 45 ml conical centrifuge tube containing 30 mL of deionized water. The soil and water were mixed until a slurry formed and the pH was measured with using a sympHony™ B10P benchtop pH meter. This method of determining soil pH was in accordance with California Test 643 (CALTRANS, 1999).

To verify the accuracy of the sympHony™ B10P benchtop pH meter, pH measurements of four sample soils were collected using four different pH reading probes as shown in Figure 3-3. Other than a single outlier, using the Accumet Basic AB15 the pH measurements at each site showed to have an average precision of ±0.2 pH, which was deemed acceptable.

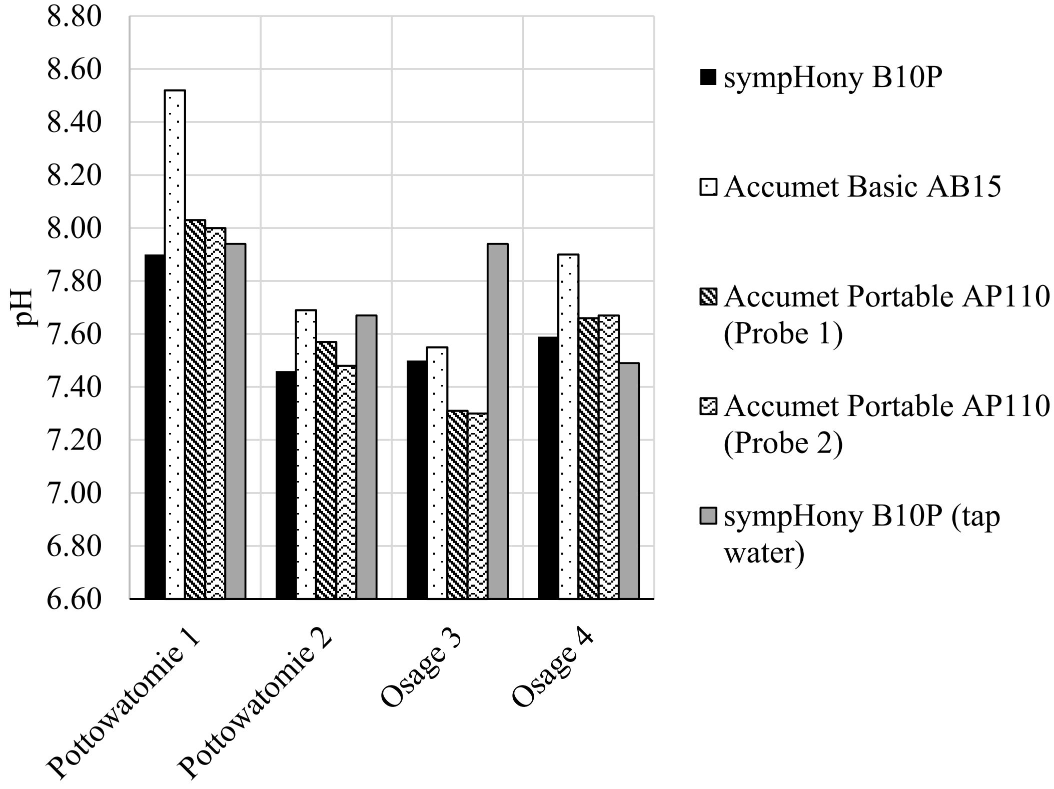

Figure 3-3: Accuracy Testing of pH Probes

After taking field and lab measurements of the pH and resistivity, an estimation of the service life of the CMPs was made using Equation 3.1 for pH less than 7.3 and Equation 3.2 for pH greater than 7.3 (CALTRANS, 1999). The predicted service life, Y was where,

$$Y = 13.79[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \qquad (3.1)$$

$$Y = 1.47\, R^{.41} \qquad (3.2)$$

where R is the lowest measured resistivity of soil or water samples taken from the field, and pH is the most acidic measured value of the soil and water samples (CALTRANS, 1999). The predicted service life was compared to the observed condition and to the service life estimates from Stratton et al. (1990).

A variation of the Volatile Solids test was conducted using raw soil sample to determine the amount of organic matter in the soil sample. The sample was tilled several times using a trowel before soil was taken at three different points and mixed for testing to ensure organic content of the soil was uniform. The sample was dried at 105° C (221° F) for one hour to remove any moisture from the sample and then placed in a desiccator for storage until it equilibrated to room temperature. The mass of the soil and container were measured before being placed in an oven at 550° C (1022° F) for 20 minutes. The samples were placed in a desiccator and left to cool at room temperature once the test was complete. Approximately 24 hours later the soil and dish was again measured. The total amount of volatile solids was

$$\text{mg volatile solids/g dry sample} = \frac{(A-B)}{A-C} \times 1000 \qquad (3.3)$$

where, *A* is the weight of soil and dish before ignition at 550° C (1022° F), *B* is the weight of soil and dish after ignition at 550° C (1022° F), and *C* represents the weight of the dish (Rice et al., 2012).

To investigate the organic composition of water collected in the field, the chemical oxygen demand (COD) test was performed. COD is a measurement of the amount of oxidant that reacts with the sample, which indicates the level of biological activity (Rice et al., 2012). A 2 mL sample of water was pipetted into COD test kit vials before being mixed thoroughly and placed in a 150° C (302° F) heating apparatus for two hours. After heating the vials allowed to cool for 20 minutes, exterior cleaned with a kin wipe, and placed in a spectrophotometer for measurement.

An initial measurement of ion content was determined to understand the nature of electrolytes contributing to the corrosive process in the pore fluid. To obtain the pore water ion content, 1 mL of the soil slurry was filtered through a .2 µm filter and pipetted into 1.5 ml vials.

The samples were then analyzed using ion chromatography performed by the Kansas State University Soil Testing Laboratory for concentrations of chlorides, sulfates, nitrates and cations.

To simulate soil conditions in the field a leachate test was performed; 100 g of soil sample was weighed and placed in an Erlenmeyer flask and submerged in one liter of deionized water. The soil-water solution was vigorously shaken to suspend soil particles. The sample was then left to settle for 24 hours. Filtered samples were taken from the soil-water slurry for ion concentration testing. Samples were also taken for COD and pH testing. Water was removed from the Erlenmeyer flask and one liter of new deionized water was reintroduced. Again, the solution was vigorously shaken to suspend the soil particles and left for 24 hours before collecting water samples for testing. The purpose of bathing the soil in water was to determine what anions were easily mobilized when introduced to water in the field. The ions that are freely mobilized within the pore water fluid would have a greater charge carrying potential, thus leading to corrosion. The pH and COD of the leachate water was also measured to determine the effects of saturation.

Chapter 4 - Results

4.1 Observed CMP Data

A total of 80 CMPs were surveyed in KDOT districts one and four between 2016 and 2017, with the goal of creating an even spread of observational pipe data based on age. A numerical rating was assigned for the crown, side, invert and exterior for every surveyed pipe following the Stratton et al. (1990) methodology. Figure 4-1 shows the ratings of each surveyed pipe versus its estimated age. From this data, small trends are observed for the side crown and exterior ratings. Ratings for these pipe locations are relatively high, with the majority of ratings above 60. A trend of slight deterioration of rating with age was observed for side, crown and external ratings for pipes installed within the last 60 years. Pipes 60 years and older were observed having ratings that deteriorated rapidly with age. Invert observations varied widely with no trend observed for the invert rating based on the age of the pipe. This study's results suggest that while the side, crown, and exterior's condition decays based primarily on age, the invert's rating is not primarily dependent on age and must be influenced by other location dependent factors.

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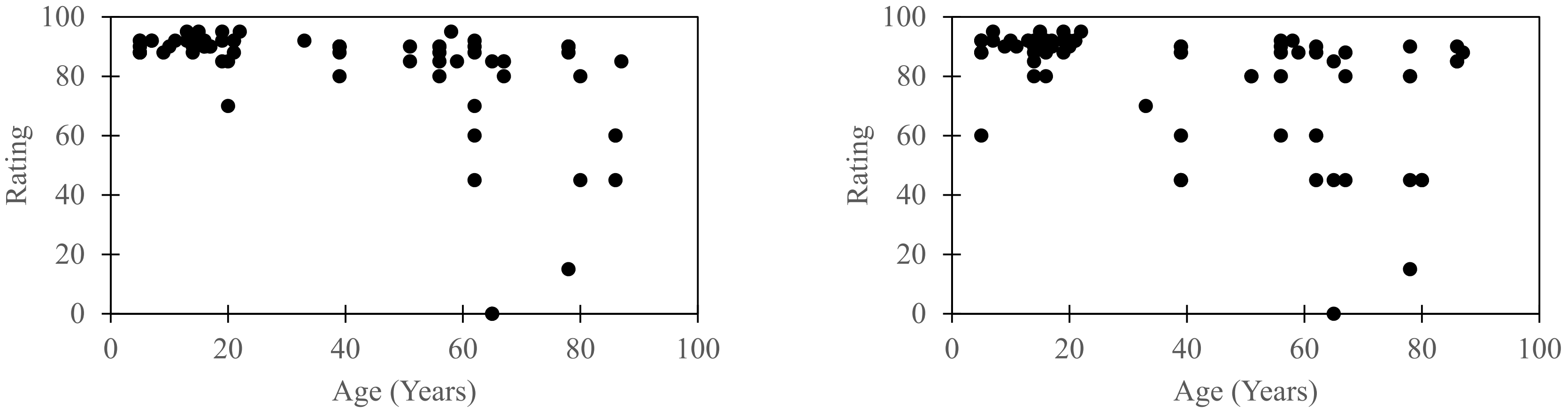
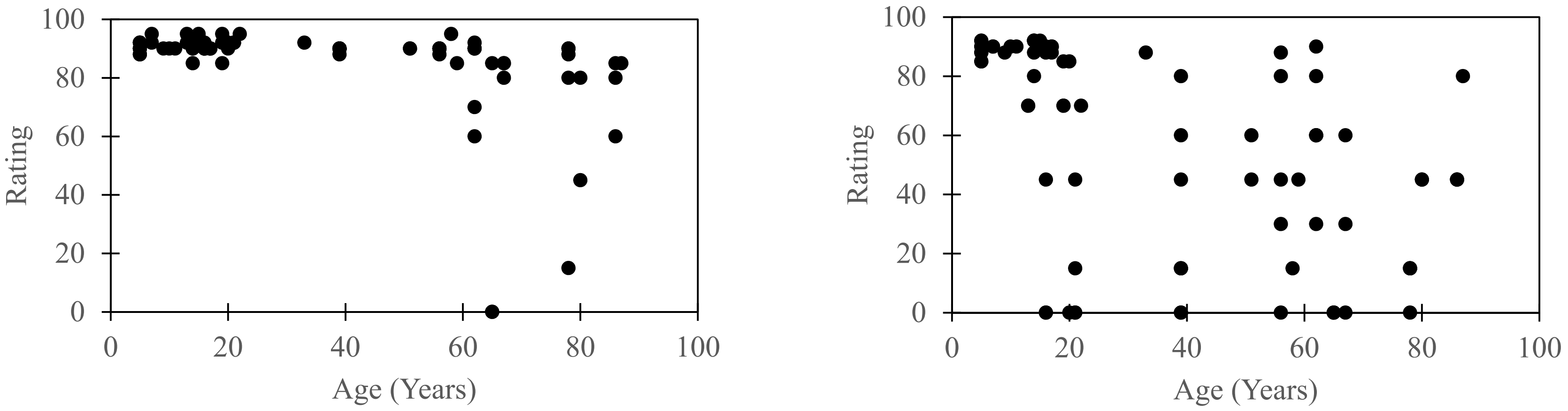


A.) Side

C.) External

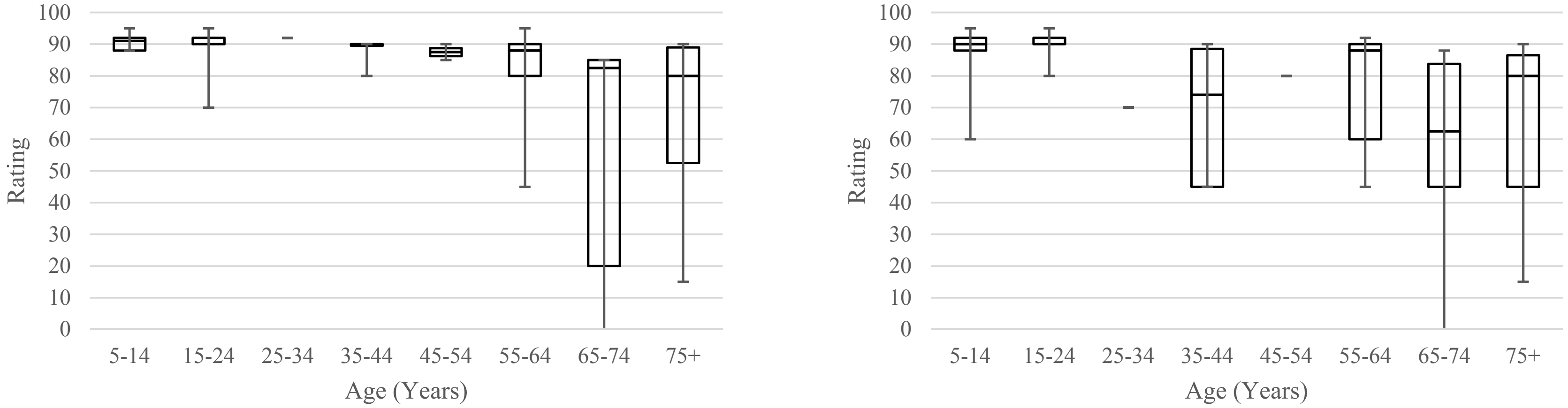


B.) Crown

D.) Invert

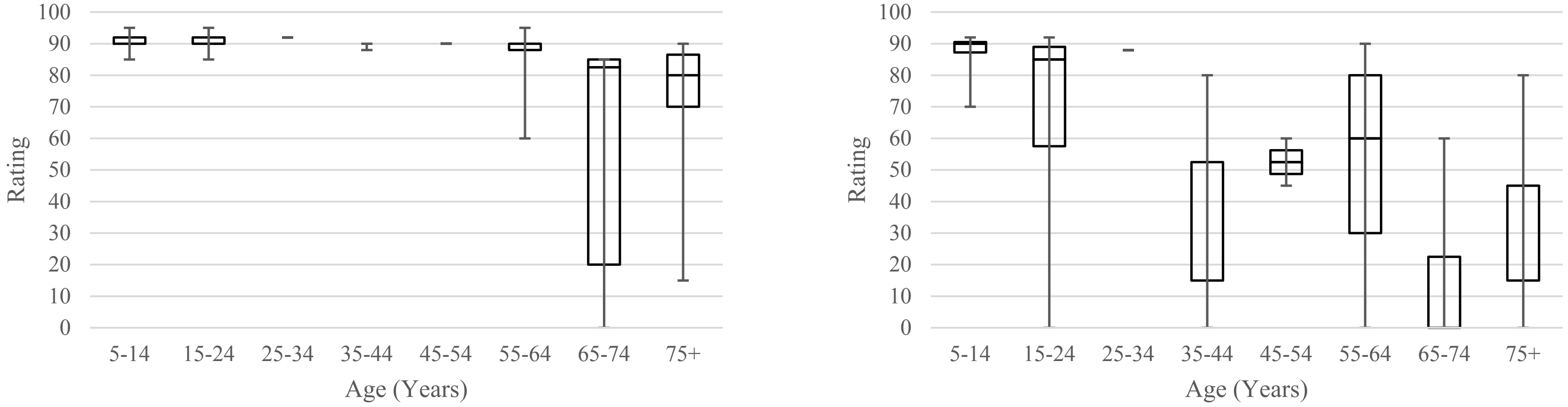
Figure 4-1: Observed Rating versus Age

Box plots of the distribution of assigned numerical ratings versus year is presented for each of the four analyzed CMP locations in Figure 4-2. These boxplots show the likely range of variation outlined by the box, the median value as shown by the line inside the box, and maximum and minimum values from the data as the outer lines extending from the box. From the box plot, a trend of variability can be seen with age for side and crown ratings. This is to be expected since the crown and side areas may not be in constant contact with soil and/or water, but are continually exposed to air humidity, precipitation, and air contaminants. The external and invert ratings of CMPs showed considerably more variability in ratings.



A.) Side

C.) External



B.) Crown

D.) Invert

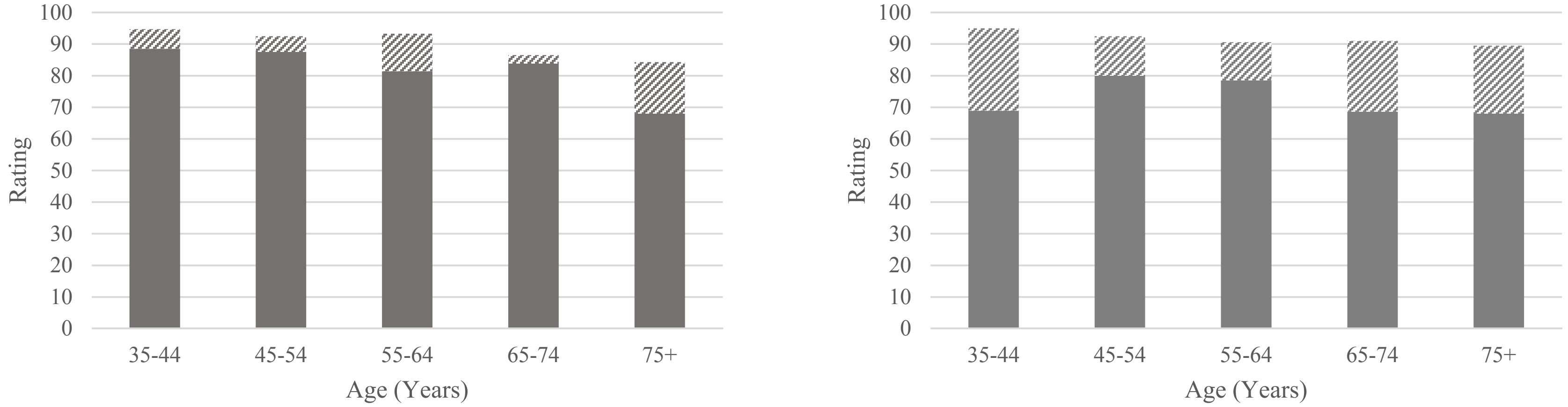
Figure 4-2: Box Plot of Rating versus Age Group

During the course of field survey, other factors were observed to contribute to accelerated deterioration of CMP. A number of CMPs were observed to have been physically damaged due to being run over by mechanical equipment as shown in Figure 4-3. These CMPs usually showed signs of corrosion where parts of the surface were sheared off. Accelerated corrosion was observed at locations where CMP seams were disjointed, which likely resulted in exposing areas of metal with insufficient protective coating. Several sites were observed to have large amounts of silted deposits in the invert as shown in Figure 4-3**.** Invert readings were still recorded for the majority of sites where silting had occurred by removing soil with a shovel. It was noted that during the field survey pipes that had large amounts of silting usually displayed large amounts of corrosion in the invert. Inverts where readings could not be taken due to excessive silting were excluded from the invert ratings data sets. CMPs where invert readings could not be taken due to standing water was also noted and excluded from invert data sets.

Figure 4-3: Example CMPs with Non-Corrosion Induced External Damage and Invert Silting

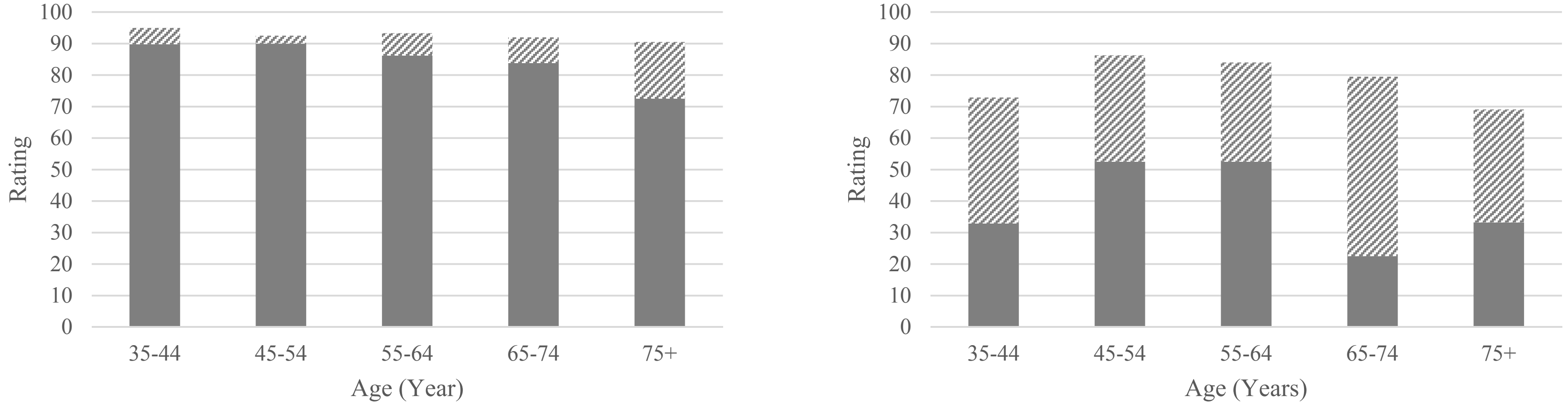
4.2 Comparison to Previous KDOT Data

An effort was made to locate and rate CMPs that had been surveyed by Stratton et al. (1990) to observe the trends of deterioration. A comparison between the ratings of the Stratton et al. study and the ratings of the 2016 survey are shown in ten-year subsets in Figure 4-4. The average rating of the 2016 study (solid) was plotted against the average rating of the same age subset taken corresponding to the 1990 study (hatched). From this data, the invert appears to have degraded more than any other location on the CMPs since the previous study took place. It was determined that the CMP's overall performance and durability would be greatly controlled by the invert's susceptibility to corrode. It was also observed during this study that although the invert had displayed the most deterioration, the majority of CMP locations had been observed to be under dry conditions as shown in Figure 4-5. Because the majority of CMPs were not observed to be subjected to prolonged periods of contact with water, it suggests that other factors besides excessive contact to moisture played a key role in the rapid deterioration of the CMP's inverts compared to other areas of the CMP.



A.) Side

C.) External



B.) Crown

D.) Invert

Figure 4-4: Observed Deterioration Since 1989

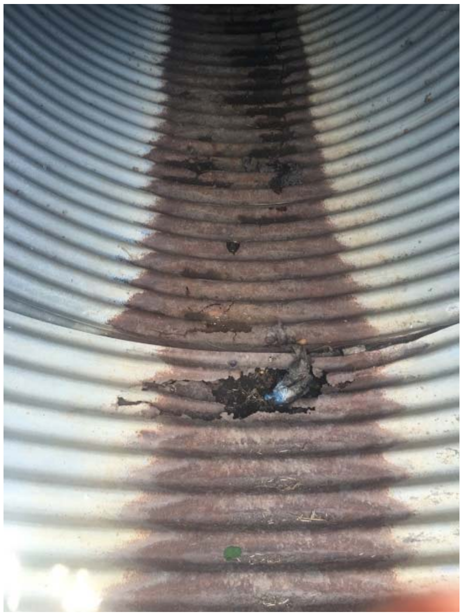


Figure 4-5: Severe Invert Corrosion under Dry Conditions

Stratton et al. (1990) concluded that due to a policy change allowing for a lighter gage of pipe, galvanized CMPs installed since 1975 have undergone increased corrosion rate as shown in Figure 4-6. Part of this study was to validate those findings based on the current field survey. This conclusion was validated by comparing the average deterioration rates of the CMPs observed in this study using Equation 4.1. Using the field observations, the rate at which the CMP's invert was deteriorating (D) was found as,

$$D = \frac{100 - R_{2016}}{Age_{2016}} \quad (4.1)$$

where, R_{2016} is the invert rating taken in the summer of 2016 and Age_{2016} being the age of the pipe at the time the invert rating was reported. Using this method the average deterioration rate of galvanized CMPs installed before 1975 is .92, while the average deterioration rate of CMPs installed in 1975 and later 1.49.

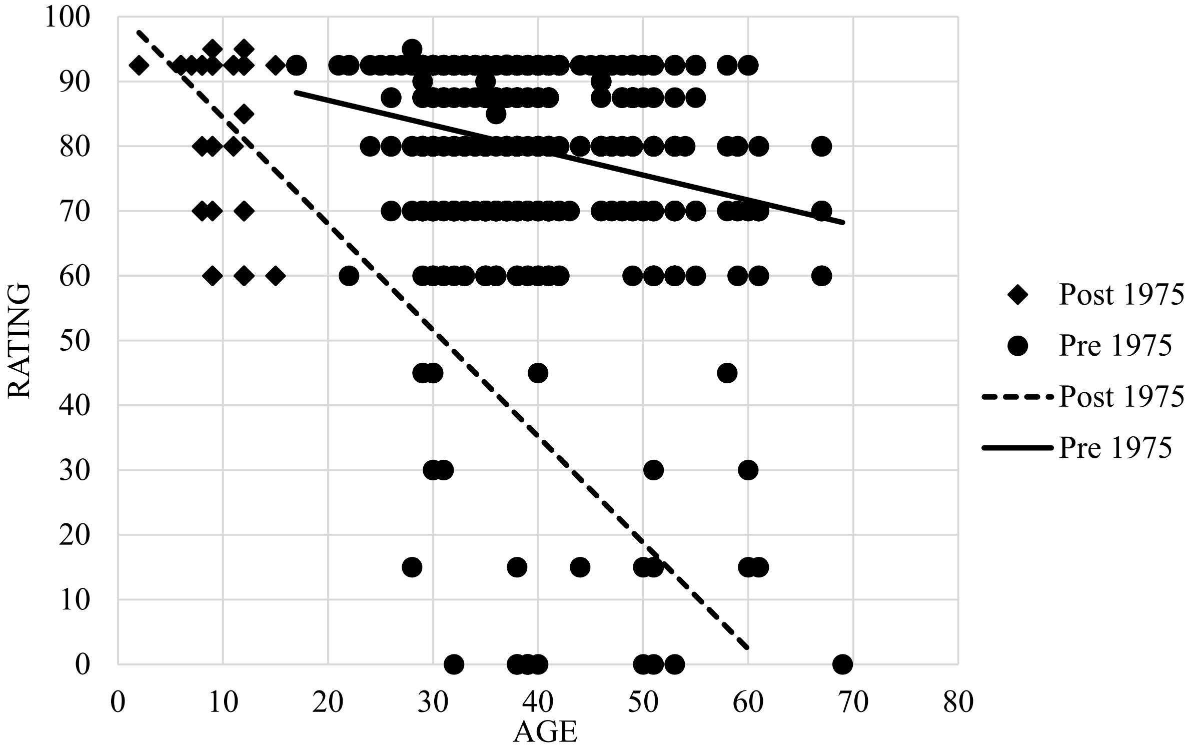


Figure 4-6: Invert Ratings in 1989 (Stratton et al., 1990)

4.3 Comparisons of Calculated Deterioration Rates to Estimated Service Life

To determine the effectiveness of field resistivity and pH measurements in predicting the service life of CMPs, results of field-testing performed by Stratton et al. (1990) were analyzed by calculating the deterioration rate of the CMPs and comparing that to the deterioration rate predicted by the California Test 643.

Stratton et al. (1990) conducted field and laboratory testing to determine pH and resistivity for a sample of the 819 locations observed in the report. A total of 34 sites were used for field and laboratory testing in Districts one and four (see Appendix A). Using the observed invert rating given by Stratton et al. (1990), the invert deterioration rate D_{1989} was calculated,

$$D_{1989} = \frac{100 - R_{1989}}{Age_{1989}} \qquad (4.2)$$

where R_{1989} is the invert rating assigned by Stratton et al. (1990) and Age_{1989} is the age of the pipe at the time of the 1989 report. This assumes that a newly installed CMPs would be given an invert rating of 100, and that the invert deteriorated at a constant rate through time. The invert deterioration rate D_{1989} was compared to the measured pH and resistivity with the results shown in Figure 4-7 and Figure 4-8, respectively. No correlation between the deterioration rate of the invert, pH and resistivity was observed in the sample provided by Stratton et al. (1990).

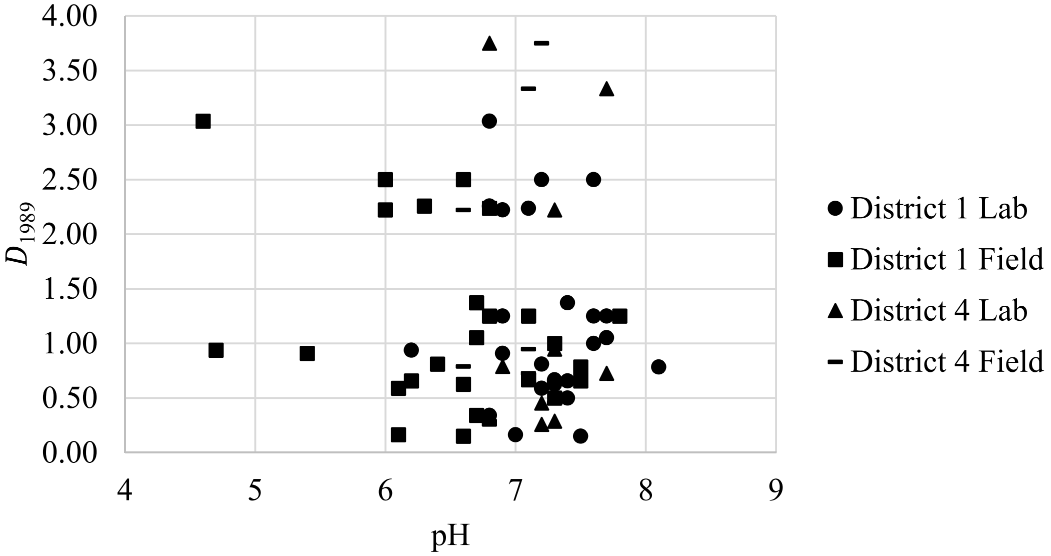


Figure 4-7: Deterioration per Year versus Measured pH

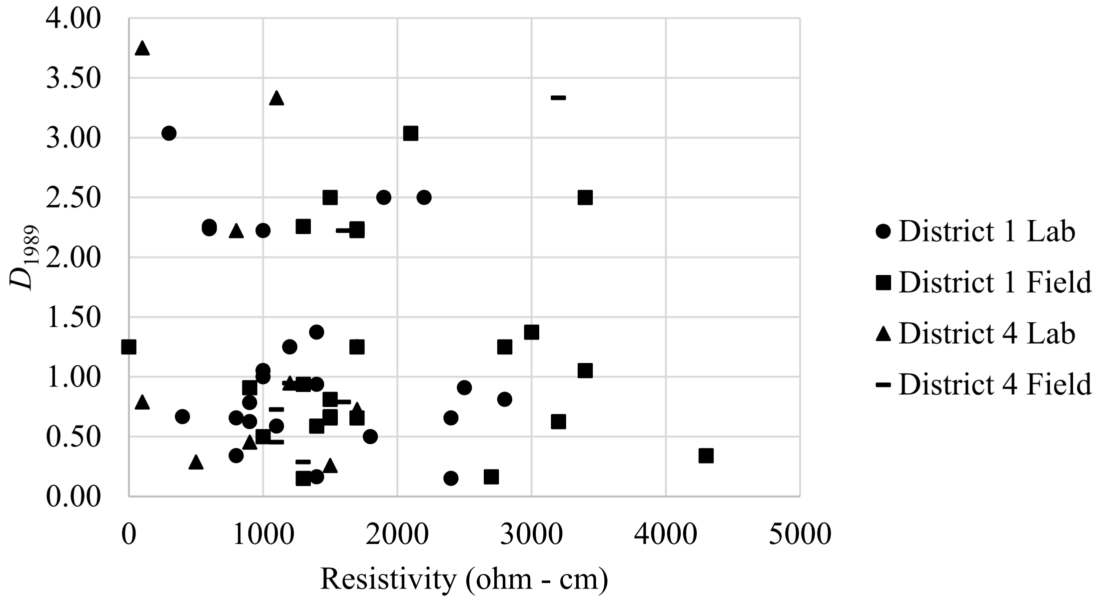


Figure 4-8: Deterioration per Year versus Measured Resistivity

The deterioration rate D_{1989} was compared to the predicted deterioration rate using the California Test 643 empirical service life formula. The deterioration rate predicted by the California Test 643 formula D_C was,

$$D_C = \frac{85}{Predicted\ Service\ Life} \qquad (4.3)$$

where 85 is the difference in rating between a newly installed CMPs (100) and a rating given to an invert showing signs of perforation (15) based on the Stratton et al. observed grading rubric. The $Predicted\ Service\ Life$ was found using the empirical formula,

$$Predicted\ Service\ Life = 1.47R^{.41} \qquad (4.4)$$

for sites where pH is measured to be greater than 7.3, and

$$Predicted\ Service\ Life = 13.79[\log_{10} R - \log_{10}(2160 - 2490 \log_{10} pH)] \qquad (4.5)$$

for sites where pH is measured to be 7.3 or less. A multiplicative factor of 1.3 was used in accordance with California Test 643 under the assumption that a 16-gauge minimum coating thickness was used on the majority of the sample set as per KDOT policy at the time. The observed invert deterioration per year D_{1989} was compared to the predicted invert deterioration per year D_C in Figure 4-9. It was shown that the predicted life using the Caltrans method consistently conservatively overestimates the observed invert deterioration. This was evidence that standard resistivity and pH measurements may not provide an accurate estimate on the corrosive potential of a site, and that other field or laboratory methods may provide better service life estimates.

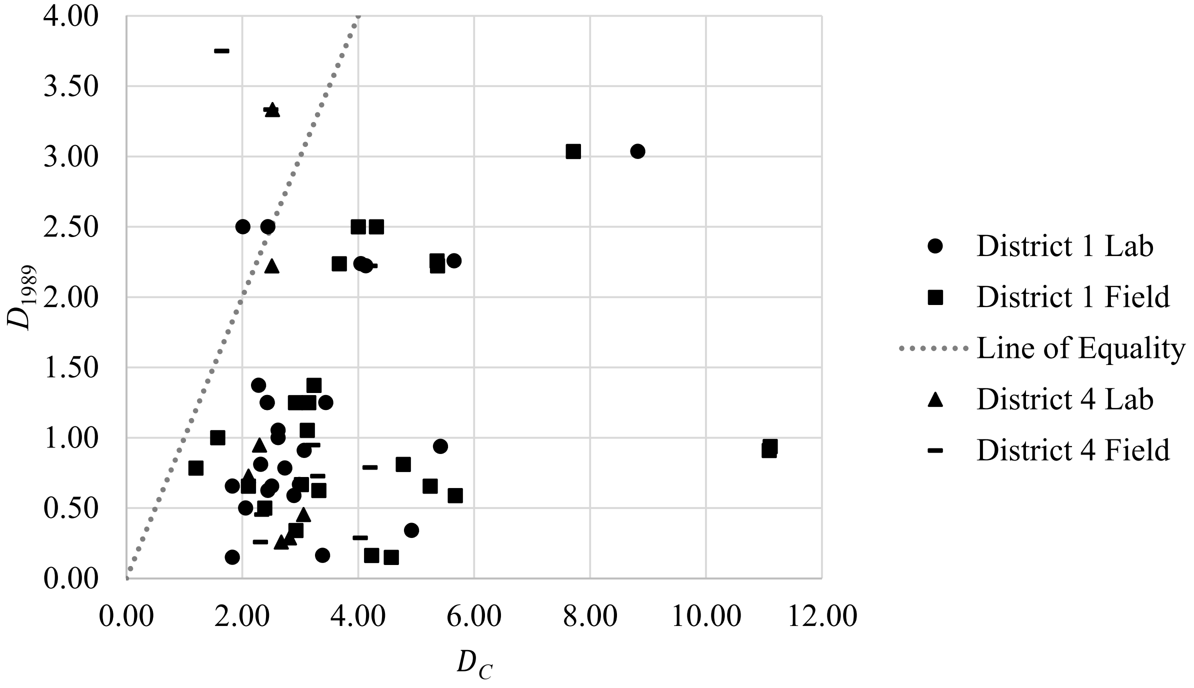


Figure 4-9: Observed Invert Deterioration versus Predicted Invert Deterioration

4.4 Leachate Testing

Due to established empirical formulas using traditional field pH and resistivity measurements not accurately predicting the observed deterioration of CMPs in the field, other soil characteristics were considered for better predicting the service life. With the vast majority of CMPs observed to be in dry conditions, water samples could not be taken. This prompted a laboratory study to understand the corrosive potential of water transported in the invert after coming into contact with surrounding soil in the form of leachate. Four locations were identified for soil sampling: two from Pottawatomie County; two from Osage County. The locations were selected based on the differences of deterioration over the past 27 years. The ratings of both studies are outlined in Figure 4-10.

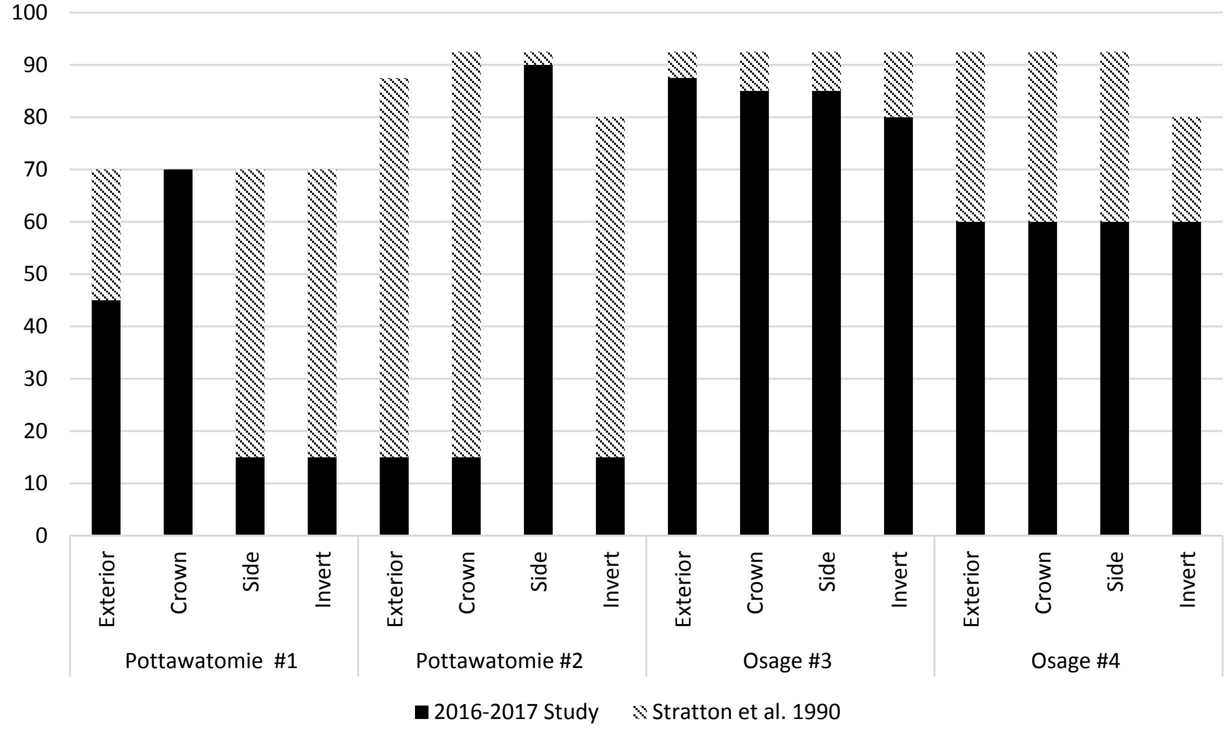


Figure 4-10: Observation Ratings of Sample Pipes

Initial field pH and soil resistivity measurements were taken at the time of pipe survey for the four sample CMP locations. Results of both pH and resistivity measurements vs CMP invert deterioration rate are shown in Figure 4-11 and Figure 4-12, respectively. No significant trends were observed between invert deterioration, pH, and resistivity.

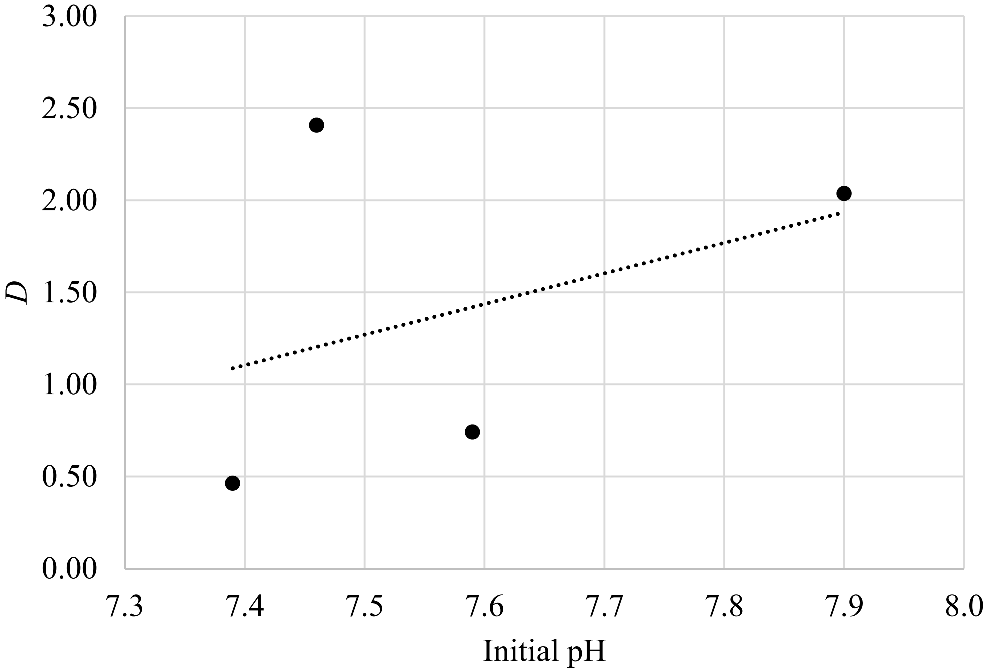


Figure 4-11: Deterioration Rate versus Initial pH

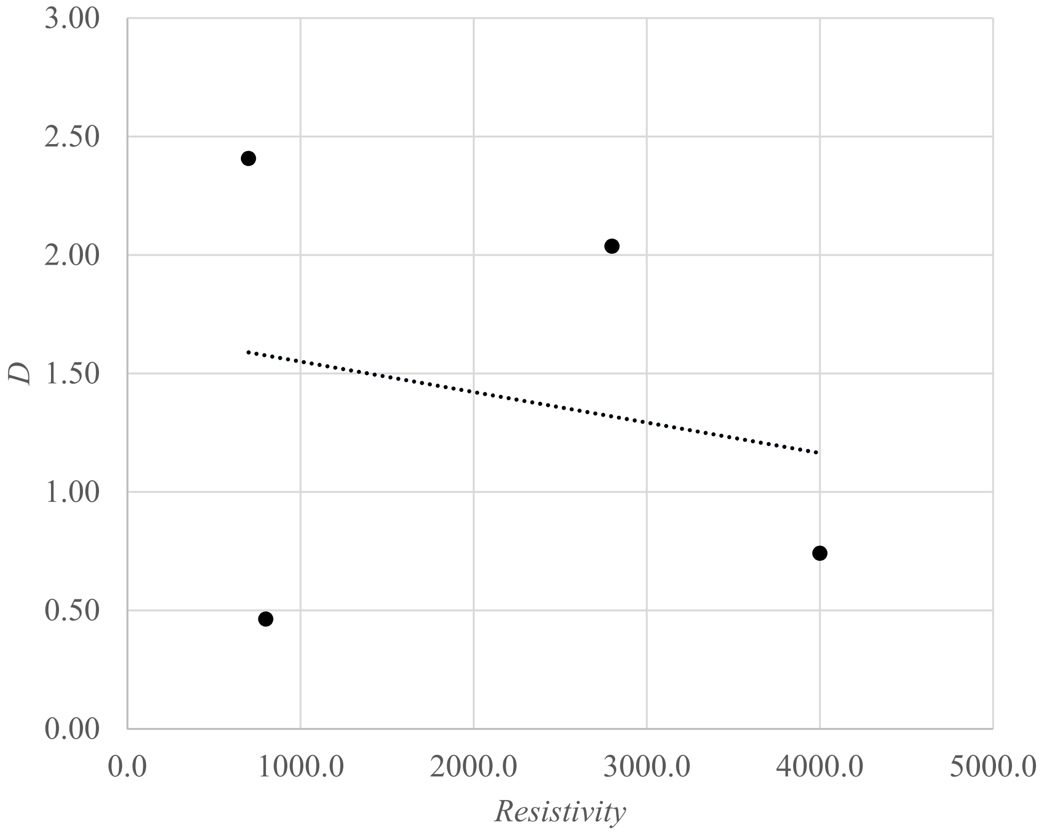


Figure 4-12: Deterioration Rate versus Initial Resistivity

Anions of soil slurry in deionized water was measured using ion chromatography, with the results shown in Table 4-1 and Figure 4-13. Relative to the other anion concentrations it was determined that chloride and sulfate anions most easily mobilized after initial contact with water, thus having the greatest presence in water flowing through the CMP's invert after coming into contact with outside soils.

Table 4-1: Initial Anion Study of Leachate Water

Samples	Fluoride (mg/L)	Chloride (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)
Pottawatomie # 1 DI	0.33	66.07	4.08	2.31	6.34
Pottawatomie #2 DI	0.07	126.98	9.80	2.22	10.68
Osage #3 DI	0.28	109.42	2.13	2.34	12.20
Osage #4 DI	0.13	46.90	75.43	Non-detectable	49.33
Pottawatomie #1 TAP	Non-detectable	350.18	5.31	2.50	51.00
Pottawatomie #2 TAP	0.10	182.60	3.78	2.10	54.70
Osage #3 TAP	0.27	91.36	3.42	2.04	49.87
Osage #4 TAP	0.16	54.70	22.09	Non-detectable	80.62

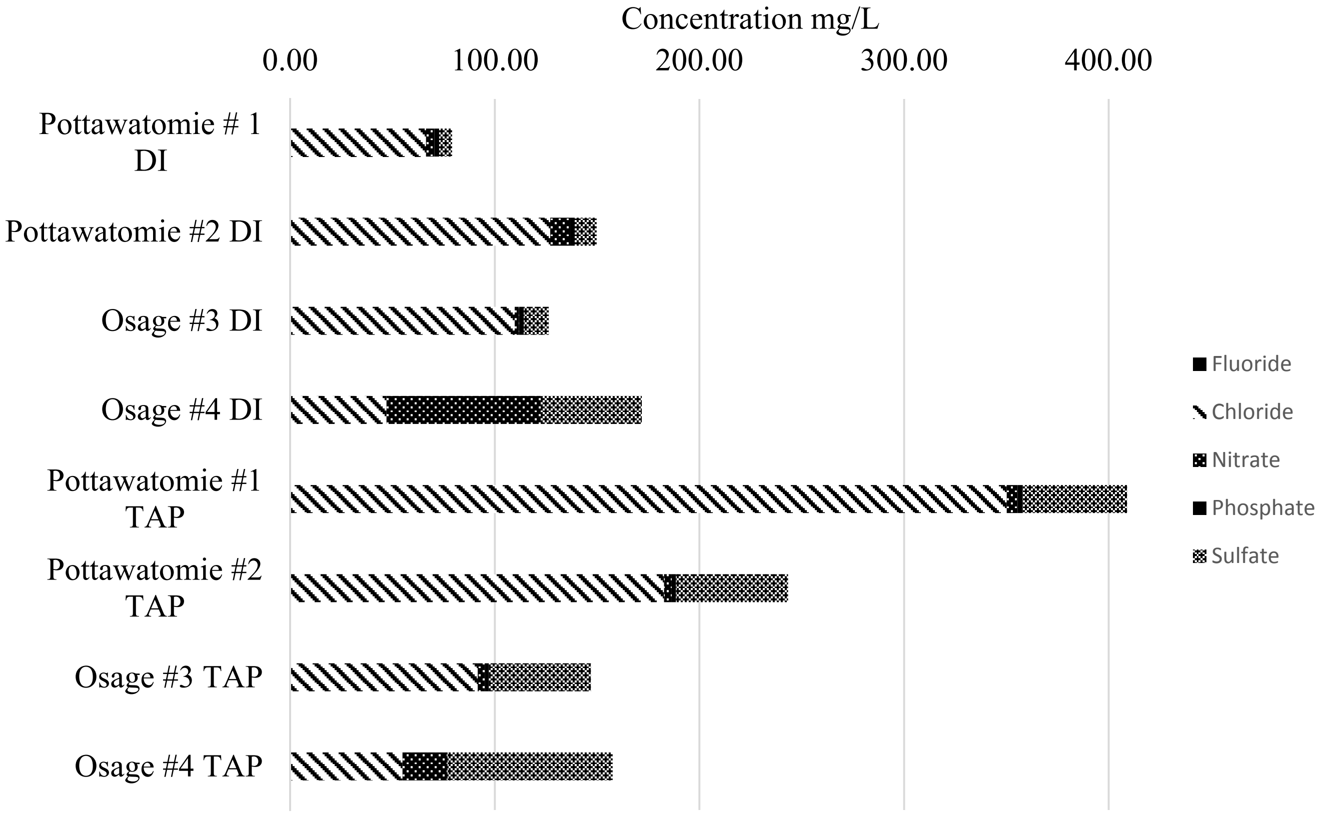


Figure 4-13: Initial Anion Concentrations

Figure 4-14 shows the results of the initial COD measurements with that of the measured volatile solids in an effort to determine the significance biological agents had on invert deterioration. No correlations were found between COD, volatile solids and invert deterioration rate in the initial study.

Tap water was also used as a medium in the study to determine if it could also be used to efficiently mobilize anions for future testing. The tap water medium was shown to be ineffective due the variability of anion concentrations when compared to the tap water control sample. Leachate resistivity measurements suggests that the deionized water would also provide a more accurate representation of anion mobilization due to the large ion gradient which is evident by the large change in resistivity after exposure to the soil sample.

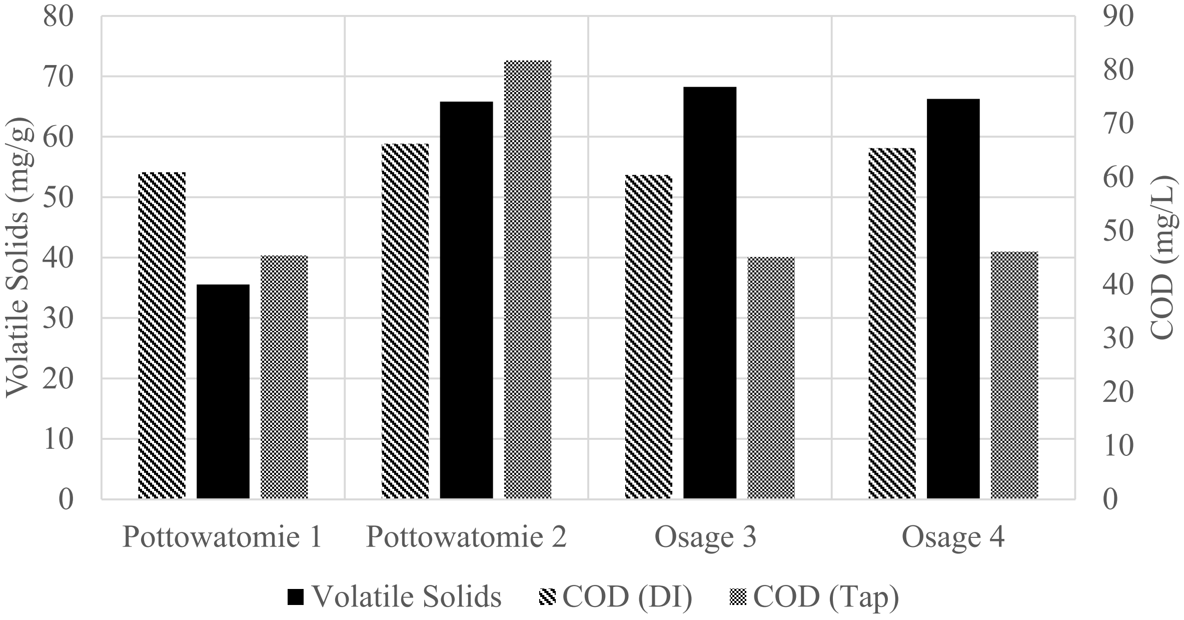


Figure 4-14: Summary of Initial COD and Volatile Solids Test

A leachate test was conducted to recreate field conditions in the laboratory: pH, resistivity and anion concentration of the water samples were measured after each trial. The results of the resistivity testing shown in Figure 4-15.

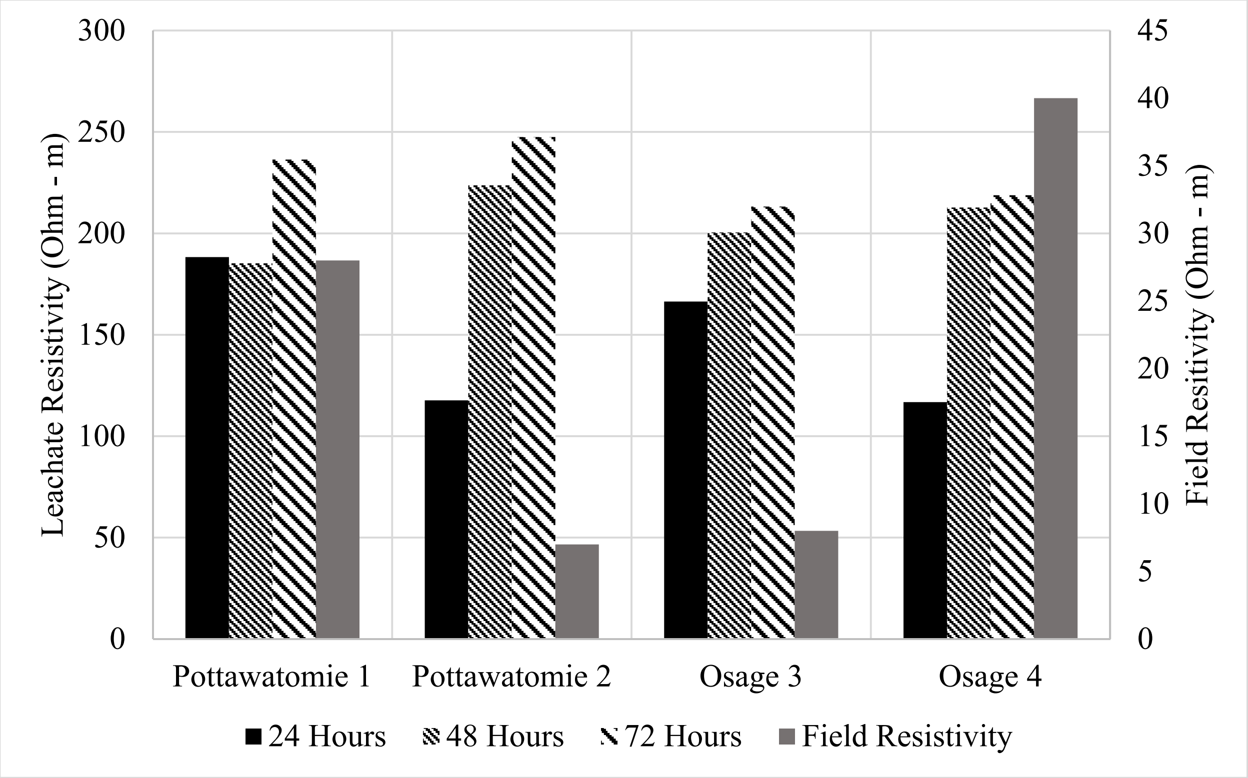


Figure 4-15: Resistivity of Leachate Trial Testing in Deionized Water Medium

The pH of leachate samples was taken after each trial using a deionized water source with a measured pH of 7.75 (shown in Figure 4-16). The pH of leachate samples was observed to be consistent between both water mediums. Unlike the Osage county, the pH samples taken from Pottawatomie counties both showed a trend of decreasing acidity after each trial wash.

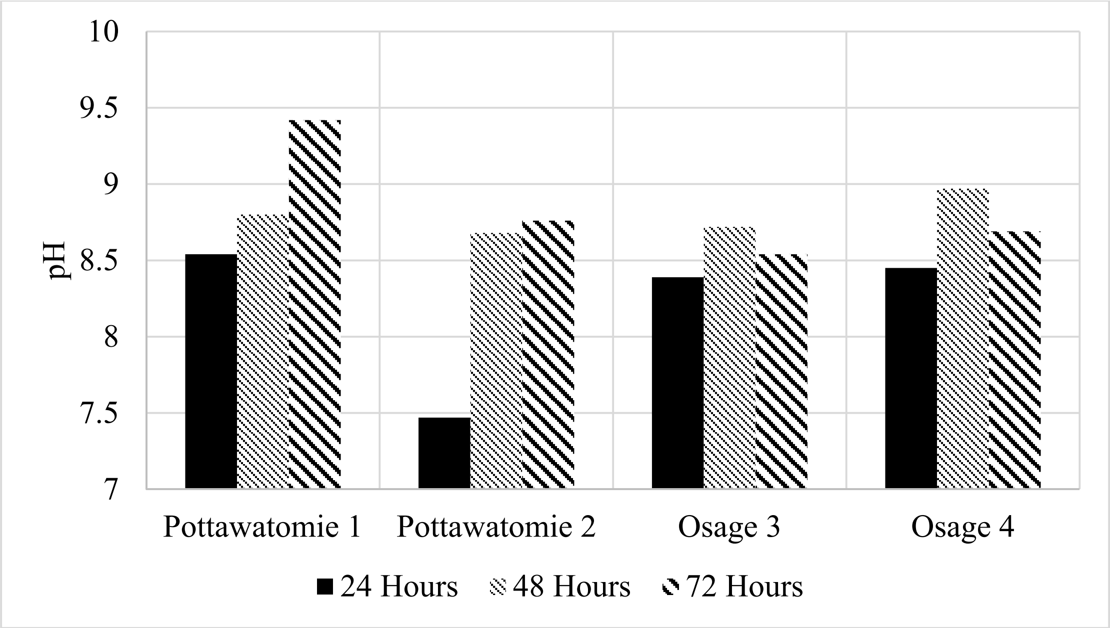


Figure 4-16: pH of Leachate Trial Testing in Deionized Water Medium

The pH measurements of the leachate samples were compared to the invert CMP deterioration per year. The change of pH for each bath was compared by finding the deviation S_{pH} for each sample location. The deviation S is

$$S_{pH} = \sqrt{\frac{\sum_i (y_i - \bar{y})^2}{n-1}} \quad (4.5)$$

where, n is the number of pH samples for each location (3), y_i is the pH of each bath, $\bar{y}$ is the mean average of pH of the samples. Note that S_{pH} is not a true statistical deviation, but rather a measurement created for use in this study. The CMP deterioration per year D is

$$D = \frac{R_{1989} - R_{2016}}{27\ years} \qquad (4.6)$$

where, R_{1989} is the invert rating from Stratton et al. (1990) report, and R_{2016} is the 2016 invert rating.

By comparing the observed deterioration per year versus the calculated standard deviation of pH during leachate testing, a linear trend is shown in Figure 4-17. For the sample population, CMPs that demonstrated the most deterioration, showed the most variance in the pH of leachate water during bathing tests. The correlation found between deterioration and the variance of leachate pH, along with the evidence showing no relationship exists between observed deterioration and pH taken in the field, indicates that deterioration may be controlled by the buffering capacity soil has on water it comes in contact with instead of the pH of the soil itself. Thus, simple pH measurements taken in the field would not properly estimate the amount of corrosion possible at a given site location.

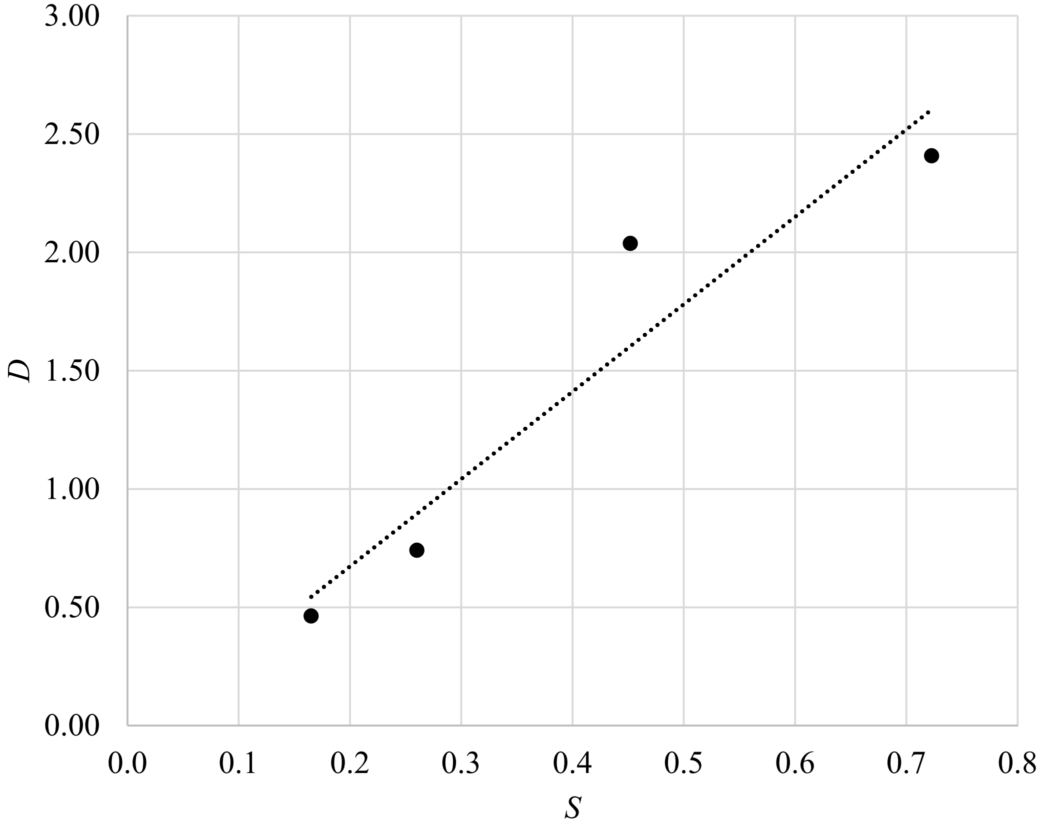


Figure 4-17: Deterioration Rate versus Variance of pH

Anion concentrations were also measured during the leachate tests. The resulting anion concentrations of leachate along with the total amount of measurable ions are shown in Figure 4-18. The results from the leachate tests suggests that for some cases ions could continuously be mobilized after initial leaching. Because ions can continuously be mobilized at relatively high concentrations, timed leachate bathing may be a greater indicator of corrosive anion activity than a singular measurement of anion soil chemistry.

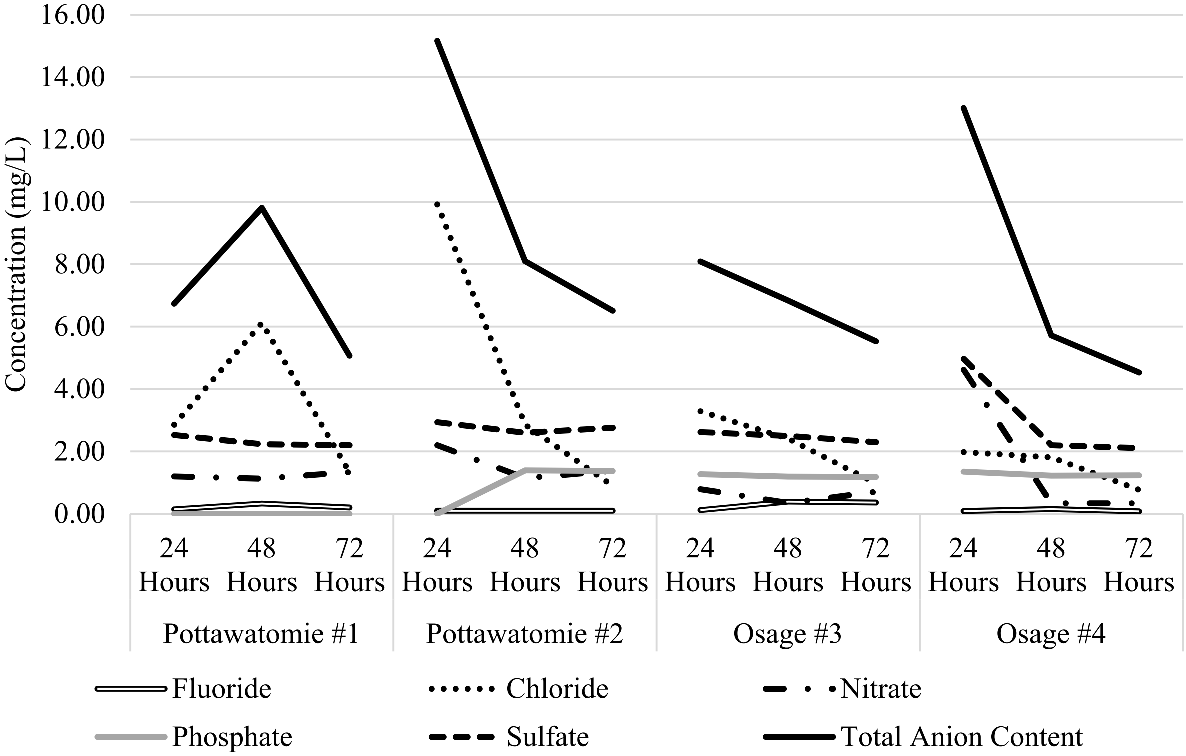


Figure 4-18: Leachate Test Anion Concentrations

The cumulative amount of anions mobilized during leachate testing is depicted in Figure 4-19. The total amount of anions mobilized during the leachate baths were compared to the deterioration rate of the invert.

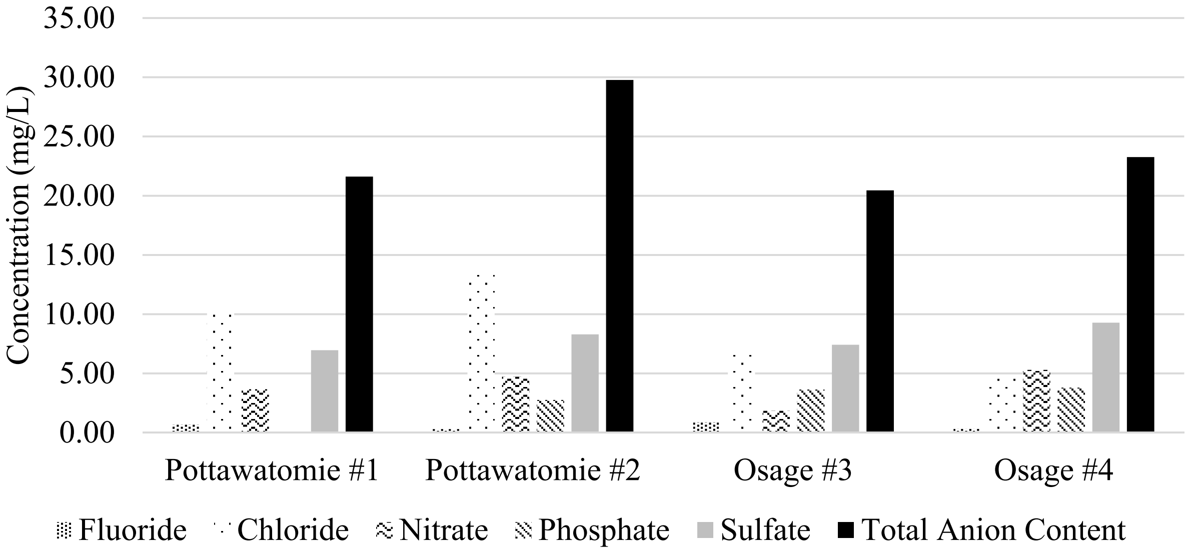


Figure 4-19: Leachate Test Total Anion Concentrations

Figure 4-20 shows that a correlation exists between the cumulative concentration of chloride that was mobilized during the leachate testing and the deterioration rate calculated at each site. The accuracy at which the cumulative chloride concentrations predicted the invert deterioration rate may prove to be a stronger indicator of deterioration then that of a typical resistivity test in the field.

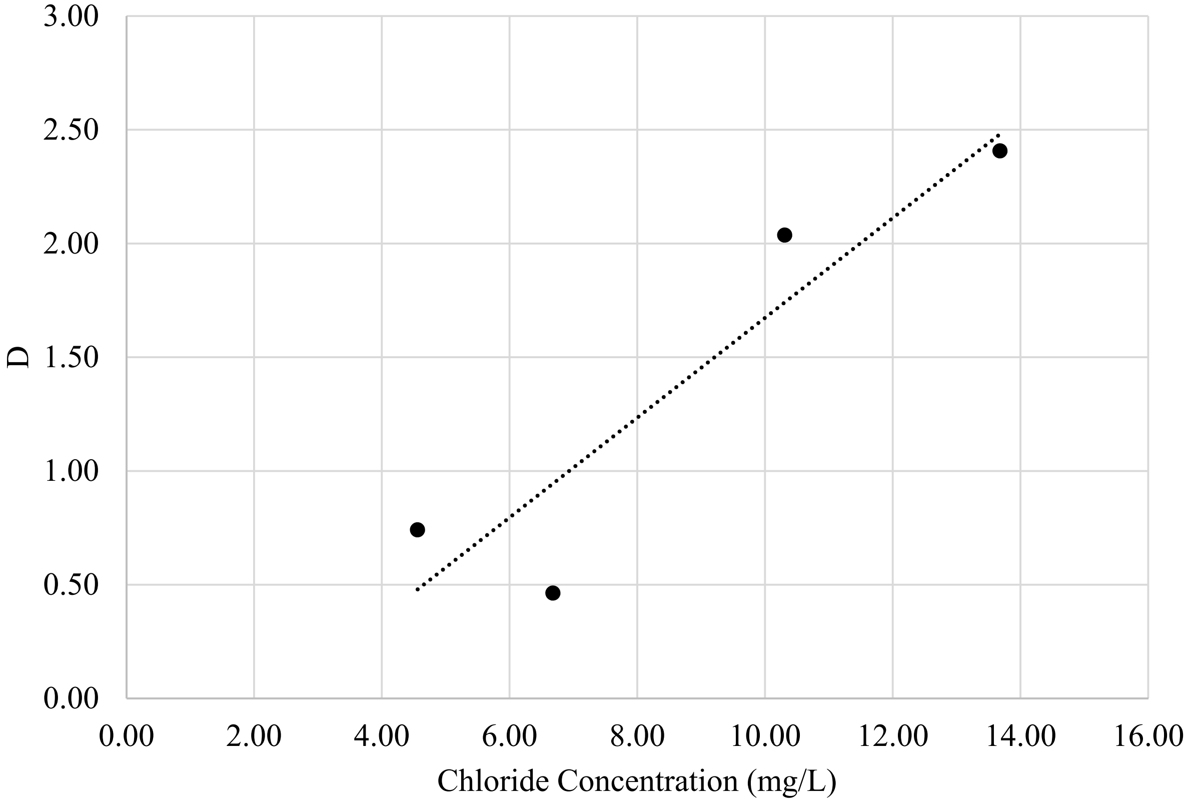


Figure 4-20: Deterioration Rate versus Chloride Concentration

Using the findings of the leachate bathing tests, an initial regression analysis was performed to create a model to describe the rate of deterioration, and ultimately the predicted service life of the CMP. The deterioration rate as found by the timed leachate bath testing described in Chapter 3 is,

$$D = 2.57\,S + \;.074\gamma_{Cl,Total} - .27 \qquad (4.7)$$

where, S is the standard deviation of the pH as described by Equation 4.5, and $\gamma_{Cl,Total}$ is the cumulative total of chloride concentrations of the leachate samples taken over 72 hours. The coefficient of determination for the proposed model is .92. The predicted service life was found using Equation 4.7 and similar assumptions made for Equation 4.3

$$Predicted\ Service\ Life = \frac{85}{2.57\ S + .074\gamma_{Cl,Total} - .27} \quad (4.8)$$

A student's t-test was performed to confirm that the chosen four samples were representative of the deterioration rates found for sites that have been sampled in both Stratton et al. and this study. At 95%, confidence it was determined that the four sites chosen for leachate testing were representative of the greater population surveyed in both studies. The results are summarized in Table 4-2.

Table 4-2: t-test Summary

	Surveyed	**Sample Pop.**
Number	40	4
Mean	1.409	1.412
Standard Deviation	0.933	0.954
Variance	0.870	0.911

t= .0065, df= 44, $p<.05$

Chapter 5 - Conclusions and Future Work

5.1 Conclusions

Since the publication of the 1990 KDOT report (Stratton et al., 1990), no studies were conducted in the state of Kansas to determine the durability of different CMPs in the field. No laboratory studies have been performed to determine how soil chemical, and biological, characteristics affect the corrosion of CMPs. Other state, and national, transportation agencies have performed various studies but the relationship between field, and laboratory, soil testing and CMP deterioration is still not well understood. There was a need to perform a field evaluation to determine how existing structures have performed recently compared to past studies, and develop new ways of measuring the corrosion potential of CMPs in the field.

A field and laboratory study was performed to better understand the performance of CMPs in the state, and how chemical and biological characteristics of soil affect the performance of CMPs. First, a field survey was performed to determine how CMPs in Kansas have performed recently compared to past studies, and to determine if policy changes have affected performance of CMPs in the field. After performing a field survey of CMPs across KDOT districts one and four a laboratory study was performed on soil taken from four sites. The chemical and biological characteristics of the soil samples were analyzed using timed soil leachate testing.

After visually observing 80 CMPs throughout the KDOT districts one and four, analyzing the deterioration rates of inverts from Stratton et al. (1990), and comparing those with the updated CMP survey, it was clear that under normal circumstances the invert deteriorated at a much faster rate than any other observed location. Further efforts in CMP surveys should focus on documenting the deterioration of the invert since it is the controlling pipe location for overall service life.

By comparing the deterioration rate of pipes using Equation 4.1 it was determined that pipes placed after 1975 were deteriorating at a much more rapid pace than pipes placed before 1975. This finding further validates the conclusion made by Stratton et al. (1990) that a KDOT material policy change had a direct influence on the performance of CMPs in the field. By using this methodology of deterioration rate comparison, it is possible to determine the how other policy shifts have influenced the performance of CMPs in the state.

Silting was noted as a considerable problem in many of the surveyed pipes. The presence of silt in the invert provides several opportunities for increased corrosive deterioration. Water becoming trapped in the soil pores exposes the metal surface to prolonged moisture, which can result in corrosion. Silted inverts containing large particles such as gravel and rock can wear on the CMPs by the process of abrasion. Inverts should be regularly cleaned by removing any debris and sediment that has collected. Regular maintenance of invert cleaning should mitigate the corrosion/abrasion effects and result in an improved service life.

By analyzing field data recorded by Stratton et al. (1990) and comparing the found deterioration rates to the predicted deterioration rate found by California Test 643, it was found that the empirical service life formula consistently over estimates the service life of CMPs. With the variability of field conditions when resistivity and pH are measured, it is recommended that further field and laboratory testing is conducted to identify soil-water parameters that may better predict CMP deterioration in the field.

The leachate testing outlined in the methodology section was done to effectively replicate the condition of water as it interacts with the soil around the CMP. By comparing the leachate samples to the invert deteriorations observed, it was possible to determine the soil-water characteristics responsible for aggressive corrosive deterioration of the invert. The sample population used in this study indicates that using the leachate testing methodology and comparing the total leachate chloride mobilized, and the standard deviation of the pH during soil washing, a correlation to invert deterioration can be made. An model for estimating the CMP's service life was developed using the total chloride mobilized and the standard deviation of pH during the leachate testing.

5.2 Future Work

To continue this research it is recommended that further field studies be done to survey more CMP sites across KDOT districts one and four. Survey sites should be used to expand the ArcGIS geodatabase that was created so that locations of surveyed pipe may be easily accessed for future field surveys. By adding more survey data, more trends of pipe performance relative to Kansas pipe policy may be made.

The results found in the soil leachate testing performed in this study are promising but need further studies to determine if correlations are statistically significant. Using the laboratory methodology outlined in Chapter 3, more site soil samples can be tested to determine if other chemical or biological characteristics can be correlated to corrosive deterioration found in the field. It is suggested that electrochemical testing also be incorporated into future studies. Electrochemical testing may provide new ways of understanding the corrosion mechanisms associated with CMP deterioration.

Like the Taylor and Marr (2012) study, soil surveys can be used to identify areas at risk of accelerated corrosion. By understanding how chemical and biological soil characteristics affect corrosion potential, current geographic soil surveys may be used to map out areas believed to pose a greater risk of corrosion. Future research should use the pipe deterioration data found from field and laboratory surveys with geostatistical data found from numerous soil surveys to predict areas that could have potential for accelerated corrosion.

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Appendix A:

Stratton et al. (1990) Field pH and Resistivity Measurements

District 1

				pH		RESISTIVITY	
NO.	COUNTY	AGE	INVT	LAB	FIELD	LAB	FIELD
1	BROWN	12	70	7.2	6	2200	3400
2	BROWN	12	70	7.6	6.6	1900	1500
3	BROWN	12	85	6.9	6.8	1700	2800
4	BROWN	30	80	7.3	7.1	400	1500
5	BROWN	33	70	6.9	5.4	2500	900
6	ATCHIS	9	80	6.9	6	1000	1700
7	JACKSO	37	70	7.2	6.4	2800	1500
8	JEFFER	38	60	7.7	6.7	1000	3400
9	DOUGLA	51	60	8.1	7.5	900	6700
10	DONIPH	50	92.5	7.5	6.6	2400	1300
11	DONIPH	38	15	7.1	6.8	600	1700
12	SHAWNE	12	92.5	7.3	6.6	900	3200
13	NEMAHA	31	30	6.8	6.3	600	1300
14	NEMAHA	34	80	7.2	6.1	1100	1400
15	NEMAHA	46	92.5	7	6.1	1400	2700
16	WYANDO	6	92.5	7.6	7.1	1200	1700
17	WABAUN	61	60	7.3	7.5	800	1700
18	POTTAW	51	30	7.4	6.7	1400	3000
19	POTTAW	28	15	6.8	4.6	300	2100
20	OSAGE	60	70	7.4	7.3	1800	1000
21	NEMAHA	32	70	6.2	4.7	1400	1300
22	NEMAHA	61	60	7.4	6.2	2400	1500
23	MARSHA	22	92.5	6.8	6.7	800	4300
24	SHAWNE	40	60	7.6	7.3	1000	10500
25	SHAWNE	32	60	7.7	7.8	1200	0

District 4

				pH		RESISTIVITY	
NO.	COUNTY	AGE	INVT	LAB	FIELD	LAB	FIELD
1	ALLEN	29	92.5	7.2	6.8	1500	9700
2	ALLEN	9	80	7.3	6.6	800	1600
3	ANDERS	44	80	7.2	7.3	900	1100
4	COFFEY	58	45	7.3	7.1	1200	1200
5	LINN	26	92.5	7.3	6.8	500	1300
6	NEOSHO	38	70	6.9	6.6	100	1600
7	MIAMI	12	60	7.7	7.1	1100	3200
8	WILSON	8	70	6.8	7.2	100	19000
9	GREEN	55	60	7.7	7.1	1700	1100

Appendix B:

Results of the 2016 Field Survey

County	Route	Diameter	CMP Material	Age	General Condition	External Rating	Crown Rating	Side Rating	Invert Rating	Resistivity
AL	US-59	24	Galvanized	56	Poor	92	90	90	45	2700
AL	US-59	24	Galvanized	56	Poor	90	90	90	30	2000
AL	US-59	24	Galvanized	56	Good	80	90	80	80	900
AL	US-59	24	Galvanized	56	Fair	88	88	85	88	1500
AL	US-59	24	Galvanized	56	Failed	60	90	88	0	3400
BR	US-36	72	Galvanized	39	Poor	45	90	90	15	1500
BR	US-36	72	Galvanized	39	Good	60	90	90	X	1500
BR	US-36	72	Galvanized	39	Adequate	45	90	90	60	1100
BR	US-36	54	Galvanized	39	Adequate	45	90	90	45	3400
BR	US-36	54	Galvanized	39	Failed	88	90	90	0	2800
BR	US-36	60	Galvanized	39	Fair	90	88	88	15	4100
BR	US-36	42	Galvanized	39	Good	90	90	90	80	X
BR	US-36	42	Galvanized	39	Poor	88	90	80	15	4000
DG	K 10	48	Galvanized	20	Fair	92	92	70	X	2000
DG	K 10	24	Galvanized	19	Good	95	95	95	70	1000
DG	K 10	24	Galvanized	19	Good	92	92	92	70	1000
DG	K 10	24	Galvanized	19	Adequate	88	85	85	85	1400
DG	N 1600 Rd	48	Galvanized	13	Good	92	92	92	70	1400
DG	N 1600 Rd	48	Galvanized	13	Good	92	95	95	70	2500
DG	K 10	36	Galvanized	21	Adequate	92	92	92	45	2500
DG	River Ridge Rd	12	Galvanized	14	Adequate	80	92	92	92	2000
JA	158th Rd	24	Galvanized	14	Adequate	90	90	92	92	1500

County	Route	Diameter	CMP Material	Age	General Condition	External Rating	Crown Rating	Side Rating	Invert Rating	Resistivity
JA	158th Rd	24	Galvanized	14	Adequate	92	92	92	92	4000
JF	K-192	18	Galvanized	65	Failed	0	0	0	0	800
JF	K-192	18	Galvanized	65	Failed	45	0	0	0	12500
JF	K-192	36	Galvanized	65	Poor	85	85	85	0	5000
JF	190th St	18	Galvanized	17	Good	90	90	90	90	4200
JF	190th St	18	Galvanized	17	Good	90	90	90	90	4200
JO	US-56	60	Aluminum	7	Good	95	95	92	90	500
JO	W 199th St	18	Aluminum	15	Good	95	95	95	92	3000
JO	W 143rd St	36	Aluminum	7	Good	92	92	92	90	1200
JO	K 169	48	Galvanized	21	Failed	92	92	88	X	600
JO	K 169	48	Galvanized	21	Failed	92	92	92	0	1700
JO	K 169	24	Galvanized	21	Fair	92	92	92	15	1700
JO	K 56	30	Galvanized	22	Good	95	95	95	70	1300
LY	Road E	18	Galvanized	17	Fair	92	90	90	88	1800
NM	US-36	42	Galvanized	58	Poor	92	95	95	15	1000
OS	US-56	60	Galvanized	86	Adequate	90	60	60	45	2000
OS	US-56	60	Galvanized	86	Adequate	85	80	45	45	2000
OS	US-56	60	Galvanized	86	Adequate	85	85	60	45	2000
OS	K-170	24	Galvanized	80	Failed	45	80	80	45	2000
OS	K-170	24	Galvanized	80	Fair	45	45	45	45	4000
OS	K-170	24	Galvanized	87	Adequate	88	85	85	80	800
OS	K-31	24	Galvanized	14	Good	88	90	90	88	750
OS	Us 75	30	Aluminum	5	Fair	88	88	88	85	1000
OS	Us 75	30	Aluminum	5	Adequate	88	88	88	85	1000
PT	K-16	50 by 30 *	Galvanized	51	Fair	80	90	90	60	1200

County	Route	Diameter	CMP Material	Age	General Condition	External Rating	Crown Rating	Side Rating	Invert Rating	Resistivity
PT	K-16	50 by 30 *	Galvanized	51	Fair	80	90	85	45	1700
PT	K-63	18	Galvanized	78	Poor	45	88	15	15	2800
PT	K-63	24	Galvanized	78	Poor	90	90	88	15	5000
PT	K-63	36	Galvanized	78	Poor	80	80	90	15	2000
PT	K-63	24	Galvanized	78	Failed	15	15	90	15	700
PT	K-63	24	Galvanized	78	Failed	80	90	90	0	5900
RL	K-18	18	Aluminized	10	Poor	92	90	90	90	7000
RL	K-18	18	Aluminized	5	Good	88	90	88	88	1500
RL	K-18	18	Aluminized	5	Good	88	90	88	88	1500
RL	K-18	18	Aluminized	5	Good	92	92	92	92	4500
RL	K-18	18	Aluminized	5	Good	92	92	92	92	4500
RL	K-18	18	Aluminized	5	Adequate	92	92	90	90	4800
SN	Old Highway 75	30	Galvanized	67	Poor	80	80	80	0	1600
SN	Old Highway 75	18	Galvanized	67	Poor	88	85	85	60	1300
SN	Old Highway 75	24	Galvanized	67	Poor	45	85	85	30	1100
SN	Old Highway 75	29 by 18 *	Galvanized	59	Fair	88	85	85	45	600
SN	US-75	18	Aluminum	16	Adequate	80	90	90	45	800
SN	US-75	15	Aluminum	16	Fair	92	92	92	X	2000
SN	SW 53rd St	18	Aluminized	11	Good	90	90	92	90	X
SN	Hodges Rd	24	Aluminum	9	Poor	90	90	88	88	750
SN	I 70	30	Galvanized	14	Good	85	85	88	80	900
WB	K-99	24	Galvanized	62	Fair	90	90	45	90	1700

County	Route	Diameter	CMP Material	Age	General Condition	External Rating	Crown Rating	Side Rating	Invert Rating	Resistivity
WB	K-99	37 by 23 *	Galvanized	62	Fair	60	60	60	60	2700
WB	K-99	58 by 36 *	Galvanized	62	Adequate	45	70	70	60	1800
WB	K-99	35 by 21 *	Galvanized	62	Poor	88	90	88	30	3800
WB	K-99	24	Galvanized	62	Good	88	90	90	80	1800
WB	K 99	30	Galvanized	62	Poor	60	92	92	60	2700
WB	Keene Eskridge Rd	24	Galvanized	20	Good	90	90	85	85	3500
WB	Bodark Rd	18	Aluminum	5	Good	60	90	90	90	1400
WB	Vera Road	18	Galvanized	16	Adequate	92	90	90	90	2700
WB	Vera Road	24	Galvanized	16	Adequate	88	90	90	88	2400
WB	Vera Road	24	Galvanized	16	Fair	90	90	90	X	1500
WY	K-7	36	Galvanized	33	Good	70	92	92	88	4000