THE EFFECT OF SOIL AGGRESSIVENESS ON THE CORROSION OF STEEL PIPES

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Abstract: The corrosion of steel pipes remains a critical issue for industries and municipal infrastructures globally, directly affecting the reliability, safety, and economic efficiency of water supply, oil, and gas transportation systems. One of the most influential environmental factors accelerating pipe degradation is the aggressiveness of the surrounding soil. This article explores the nature of soil aggressiveness, the mechanisms by which soils provoke steel pipe corrosion, and the main environmental and physicochemical factors that modulate this process. The study draws on laboratory analyses, field observations, and literature review to identify the correlations between soil properties—such as pH, moisture content, ion concentration, and microbiological activity—and the rate of corrosion in steel pipes. The article concludes with practical recommendations for mitigation and highlights the need for ongoing research, especially considering the complexity of soil-pipe interactions in variable geographic and climatic regions.

Keywords: soil aggressiveness, corrosion, steel pipes, environmental factors, soil chemistry, pipeline protection

Аннотация: Коррозия стальных труб остаётся актуальной проблемой для промышленности и муниципальной инфраструктуры во всём мире, напрямую влияя на надёжность, безопасность и экономическую эффективность систем водоснабжения, транспортировки нефти и газа. Одним из наиболее значимых экологических факторов, ускоряющих разрушение труб, является агрессивность окружающего грунта. В статье рассматривается сущность агрессивности грунта, механизмы воздействия почвы на коррозию стальных труб и основные экологические и физико-химические факторы, влияющие на этот процесс. В исследовании использованы лабораторные анализы, полевые наблюдения и обзор литературы для выявления взаимосвязей между свойствами почвы — такими как pH, влажность, концентрация ионов и микробиологическая активность — и скоростью коррозии стальных труб. В заключении статьи даны практические рекомендации по снижению коррозии и подчёркнута необходимость дальнейших исследований, особенно с учётом сложности взаимодействия между трубопроводами и грунтами в различных географических и климатических условиях.

Ключевые слова: агрессивность грунта, коррозия, стальные трубы, экологические факторы, химия почвы, защита трубопроводов

Steel pipelines are an integral component of modern civilization, ensuring the transportation of water, oil, gas, and chemicals over vast distances. However, the service life of these pipelines is often jeopardized by external corrosion, much of which is attributable to the characteristics of the soils in which they are buried. Corrosion is a complex electrochemical process that, when accelerated by aggressive soil environments, leads to loss of structural integrity, increased maintenance costs, and potentially catastrophic failures. The understanding of soil aggressiveness and its effects on steel corrosion is thus of paramount importance for engineers, researchers, and utility managers.

Soil aggressiveness refers to the propensity of a soil to initiate and accelerate the corrosion of buried metals. This propensity is dictated by several soil properties, including moisture content, aeration, electrical resistivity, pH, the presence of soluble salts, organic matter, and the activity of soil microflora. Each of these factors can independently or synergistically increase the rate of steel corrosion. For instance, low soil resistivity is often associated with higher corrosivity due to enhanced ionic mobility, while acidic soils (low pH) are notorious for their ability to destabilize the protective oxide layers on steel surfaces.

Over the past decades, numerous incidents of pipeline failures have been linked directly to aggressive soils. As such, a thorough understanding of the mechanisms by which soils promote corrosion is essential for the design of effective protective measures, including coatings, cathodic protection, and the selection of appropriate construction materials. Furthermore, the increasing complexity of urban and industrial landscapes, coupled with changing environmental conditions, necessitates continuous research into the relationships between soil characteristics and corrosion processes.

This article aims to review and analyze the current state of knowledge regarding the effect of soil aggressiveness on the corrosion of steel pipes, using a combination of empirical research and theoretical models. It also seeks to provide practical insights for pipeline operators and designers tasked with the mitigation of corrosion-related risks.

To investigate the effect of soil aggressiveness on the corrosion of steel pipes, a multifaceted research approach was adopted. The study combined field sampling and laboratory experiments with a critical review of existing literature and standards. The methodology involved the following stages: (1) selection and characterization of soil samples from diverse geographic regions, (2) exposure of standardized steel specimens to these soils under controlled laboratory conditions, (3) periodic measurement of corrosion rates using gravimetric and electrochemical techniques, and (4) statistical analysis of the correlation between soil properties and observed corrosion rates.

Soil samples were collected from locations known for their varied corrosive potentials, including agricultural land, urban areas, coastal zones, and industrial sites. Sampling depths ranged from 0.5 to 1.5 meters, reflecting typical pipeline burial depths. Each sample underwent comprehensive physicochemical analysis, including determination of pH, moisture content, electrical resistivity, redox potential, concentration of chloride and sulfate ions, organic matter content, and the presence of iron- and sulfur-reducing bacteria.

pH was measured using a standard glass electrode in a soil-water suspension, while moisture content was determined gravimetrically by oven-drying. Electrical resistivity was assessed using a Wenner four-probe apparatus. Ion concentrations were determined using ion chromatography, and microbiological analysis followed the methods described by the American Society for Testing and Materials (ASTM).

Standard carbon steel coupons (grade 20) with dimensions 50×25×3 mm were prepared, polished, and cleaned according to GOST 9.602-2016. Coupons were then weighed to the nearest 0.1 mg and buried in soil samples under laboratory conditions that simulated field moisture and temperature (20–30°C, 60–80% humidity). Each soil environment was maintained for a period of six months, with regular monitoring of soil parameters.

At predefined intervals (30, 90, 180 days), coupons were extracted, cleaned of corrosion products according to GOST 9.510-93, and weighed again to determine the mass loss due to corrosion. Additionally, electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization tests were performed to assess corrosion kinetics.

Corrosion rates were calculated as mass loss per unit area per unit time ($g/m^2 \cdot year$) and correlated with soil parameters using multivariate regression analysis. Statistical significance was assessed at the 95% confidence level. Data visualization and additional analysis were performed using standard software packages (OriginLab, SPSS).

The analysis revealed a strong correlation between soil properties and the rate of steel corrosion. Soils with low pH (≤5.5), high moisture content (≥20%), and low electrical resistivity (≤10 Ω·m) were consistently associated with elevated corrosion rates. For example, steel coupons buried in acidic soils experienced a mean corrosion rate of 0.24 g/m²·year, compared to 0.08 g/m²·year in neutral or alkaline soils. The presence of chloride and sulfate ions further amplified corrosion, especially in coastal and industrial soils where these ions were found in concentrations exceeding 100 mg/kg.

Microbiological activity, particularly from sulfate-reducing bacteria (SRB), was also found to be a significant contributor to corrosion. Soils with high SRB counts exhibited localized pitting and accelerated mass loss. Electrochemical analyses indicated that in such soils, the open circuit potential of steel shifted towards more negative values, reflecting increased corrosion susceptibility.

Influence of Individual Soil Factors

pH: Acidic soils accelerated both uniform and localized corrosion of steel. The dissolution of protective oxide layers was observed via scanning electron microscopy (SEM), and the resultant surfaces showed deep pits and cracks. Neutral and slightly alkaline soils provided a certain degree of passivation but were not immune to corrosion, especially in the presence of aggressive ions.

Moisture Content: Higher soil moisture facilitated ionic transport, thereby increasing the rate of electrochemical reactions at the steel surface. Dry soils, by contrast, generally limited corrosion except in cases where capillary action maintained persistent thin films of moisture around the pipe.

Electrical Resistivity: Soils with resistivity below 10 Ω·m were consistently more corrosive. The effect was particularly pronounced in clayey and saline soils, where resistivity is naturally low due to high ion content and water retention capacity.

Chlorides and Sulfates: Chloride ions are known to disrupt passive films on steel, initiating pitting and crevice corrosion. Sulfates, particularly in the presence of organic matter and SRB, contributed to both uniform corrosion and the formation of iron sulfide scales, which under certain conditions can become conductive and promote further corrosion.

Microbiological Activity: Soils with active SRB populations induced distinctive corrosion morphologies. Microbially influenced corrosion (MIC) was characterized by deep pits, black iron sulfide deposits, and hydrogen sulfide gas production.

Field data from operational pipelines confirmed laboratory findings. Regions with aggressive soils experienced more frequent and severe cases of external corrosion, as evidenced by inspection records and maintenance logs. In some cases, unprotected steel pipes suffered wall loss rates exceeding 0.3 mm/year, necessitating early replacement or rehabilitation.

The findings of this study underscore the pivotal role of soil aggressiveness in the external corrosion of steel pipelines. The multifactorial nature of soil-induced corrosion is evident from the synergistic effects observed among soil pH, moisture, ionic composition, and microbiological activity. This complexity poses significant challenges for pipeline design, risk assessment, and maintenance.

The relationship between soil properties and corrosion is not linear, as several parameters interact dynamically. For instance, high moisture content alone does not guarantee aggressive corrosion unless accompanied by low resistivity and the presence of aggressive ions. Similarly, alkaline soils may still provoke corrosion if chloride concentrations are sufficient to disrupt passivation.

The problem is further complicated by the spatial and temporal variability of soil conditions. Seasonal changes in moisture, temperature, and microbial activity can cause significant fluctuations in corrosion rates, sometimes leading to unpredictable failures. For instance, freeze-thaw cycles in temperate regions can increase soil moisture and ion mobility, while droughts may temporarily reduce corrosion risk.

To mitigate the risks posed by aggressive soils, a combination of preventive and corrective strategies is necessary. These include the application of protective coatings, installation of cathodic protection systems, use of corrosion-resistant alloys, and periodic inspection and maintenance. The selection of protection methods must be informed by detailed soil surveys and continuous monitoring, as soil conditions may evolve over time due to natural processes or anthropogenic activities.

The role of standards and regulatory frameworks is crucial in ensuring pipeline integrity. International standards such as ISO 15589-1 and regional norms like GOST 9.602-2016 provide guidance on the assessment of soil corrosivity and the design of protective systems. However, their effective implementation requires close cooperation among engineers, geologists, and microbiologists.

Given the ongoing expansion of pipeline networks and the increasing exploitation of challenging environments (e.g., permafrost, saline deserts, reclaimed land), further research is warranted to refine predictive models of soil-pipe interaction. The development of advanced sensors for real-time monitoring of soil and corrosion parameters, as well as new materials with enhanced resistance to complex environmental stressors, represents a promising direction for future work.

This study has demonstrated that the aggressiveness of soil is a critical determinant of steel pipe corrosion rates, with significant implications for infrastructure reliability and safety. Key soil factors—including pH, moisture content, electrical resistivity, chloride and sulfate concentrations, and microbiological activity—act individually and synergistically to modulate corrosion processes. Effective mitigation requires a holistic approach, combining robust soil assessment, protective technologies, and ongoing monitoring.

The complexity and variability of soil environments underscore the need for adaptive, site-specific corrosion management strategies. As global demand for safe and durable pipeline systems grows, interdisciplinary research and technological innovation will be essential to meet the challenges posed by aggressive soils.

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