



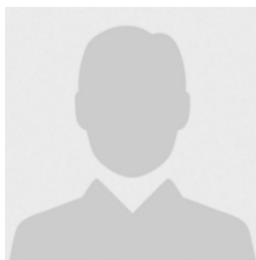
Using Random Forest for the Development of a Predictive Model for Mild Steel in Ekpoma



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current;
gas flow rate;
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Abstract

In Nigeria, buried steel infrastructure suffers premature failure due to soil-induced corrosion, yet existing degradation models rely on idealized laboratory simulations that ignore real-world soil heterogeneity and welding parameter interactions. This study addresses this critical gap by investigating mechanical property decay behavior of mild steel weldments through longitudinal field exposure in an Ekpoma soil environment, with the aim of developing robust, field-validated predictive models to enhance infrastructure durability. Field exposure tests were conducted over twelve months on 20 weldment specimens per site, with tensile strength, impact energy, and hardness evaluated post-exposure. Random Forest (RF) was trained on welding parameters (current, voltage, gas flow) using 16 samples, with rigorous validation on 4 unseen field runs. Random Forest demonstrated exceptional predictive capability across all sites and responses, achieving test-set R^2 values of (tensile), 0.821 (impact), and 0.882 (hardness). These results establish RF as a viable tool for field-based corrosion forecasting, proving that integration of real-world exposure data with ensemble learning is essential for accurate durability prediction and proactive infrastructure management in heterogeneous soil environments.

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1 Introduction

Background of the Study

Quality and productivity play an important role in today's manufacturing market. Nowadays, manufacturing industries face very stiff and cutthroat competitive market conditions in manufacturing industries ([Patel & Patel, 2014](#)). The main objective of industries is to produce better quality products at minimum cost and increase productivity. TIG welding is a vital and common operation used for joining two similar or dissimilar parts by heating the material, applying pressure, or using filler material to increase productivity with less time and cost constraints to obtain the main objective of the company regarding quality and productivity. In this study, an attempt is made to develop a predictive model for mild steel buried in Ekpoma soil.

[Li et al. \(2013\)](#), studied the Influences of heat input on the microstructure and grain size of shielded metal arc welded 316L stainless steel joints. Three heat input combinations were selected from the operating window of the shielded metal arc welding process, and welded joints made using these combinations were subjected to microstructural evaluations so as to analyze the effect of thermal arc energy on the microstructure and grain size of these joints. The results of this investigation indicate that the microstructure of the weld zone and the fusion zone is austenite and a small amount of ferrite, while the microstructure of the heat-affected zone (HAZ) is austenite and a small number of MC-type carbides, and it can be seen that the amount of ferrite in the weld zone decreases with heat input. For the joints investigated in this study, the average grain size in the HAZ increases with heat input.

[Gunaraj & Murugan \(2002\)](#), carried out a predictive study on Submerged Arc Welding (SAW), he reported that selecting appropriate values for process variables is essential in order to control heat-affected zone (HAZ) dimensions and get the required bead size and quality. Also, conditions must be selected that will ensure a predictable and reproducible weld bead, which is critical for obtaining high quality. In this investigation, mathematical models were developed to study the effects of process variables and heat input on various metallurgical aspects, namely, the widths of the HAZ, weld interface, and grain growth and grain refinement regions of the HAZ. The color metallography technique and response surface methodology were also used. Direct and interaction effects of the process variables and heat input on the characteristics of the HAZ were presented in graphical form.

[Hu & Tsai \(2007\)](#), developed a model to simulate the transport phenomena occurring during the gas metal arc welding process. An interactive coupling between arc plasma; melting of the electrode; droplet formation, detachment, transfer, and impingement onto the workpiece; and weld pool dynamics was considered. Based on the unified model, a thorough investigation of the plasma arc characteristics during the gas metal arc welding process was conducted. It was found that the droplet transfer and the deformed weld pool surface have significant effects on the transient distributions of current density, arc temperature, and arc pressure, which were normally assumed to be constant Gaussian profiles.

[Joarder et al. \(1991\)](#), carried out a detailed study on the microstructure of submerged arc (SA) weld metal and the heat-affected zone of a 1.2-cm (0.5-in.) thick plain carbon steel plate using transmission electron microscopy. The various subzone microstructures observed in the HAZ of a SA weld are spheroidized, partially transformed, grain-refined, and grain-coarsened. The grain-coarsened area exhibits predominantly Widmanstätten ferrite with pearlite, while the other subzones of the HAZ reveal polygonal ferrite and pearlite. Depending on the number, size, and distribution of inclusions, the weld metal microstructure varies.

Schneider et al. (2017), carried out a study to evaluate the influence and optimize the factors of the TIG-MIG/MAG hybrid welding process on the geometry of the weld bead. An experimental design using the Taguchi methodology (robust design method) was used to conduct the experiments. The experiments were carried out according to an orthogonal matrix with 27 experiments, with three replicates each, totaling 81 test specimens. The factors (MIG/MAG shielding gas type, MIG/MAG voltage, MIG/MAG wire feed, gas flow rate of TIG, electric current intensity of TIG, and welding speed) were varied with three levels each. Penetration, heat-affected zone (HAZ), bead width, and bead height were the response variables analyzed. The results showed that the penetration was significantly influenced by the MIG/MAG wire feed, MIG/MAG shielding gas type, MIG/MAG voltage, and welding speed. According to Thakur & Chapgaon (2016), different process parameters of Gas Tungsten Arc Welding (GTAW) affect the weldment quality. Increasing welding current increases the deposition rate and reduces the hardness. Direct current electrode negative (DCEN) polarity provides deep penetration as compared to Direct current electrode positive (DCEP) and Alternating Current (AC) polarity. An increase in welding speed decreases the bead width and depth of penetration. Popovic et al. (2010), investigated the influence of welding heat input on the weld metal toughness of a high-carbon steel surface-welded joint with a conference paper titled: The effect of heat input on the weld metal toughness of surface welded joint, using surface steel with self-shielded wire, with three different heat inputs (6.5, 10.5 and 16 KJ/cm). The author established that an increase in heat input decreases toughness, and 7KJ/cm heat input is the optimum temperature for weld metal toughness of the steel investigated.

Tabish et al. (2014), investigated the effect of heat input on microstructure and mechanical properties of the TIG welded joint of AISI 304 stainless steel in a journal titled: Effect of heat input on microstructure and mechanical properties of the TIG welded joint of NSI304 stainless steel. The authors processed different specimens with varied heat input (high, medium, and low); they examined the mechanical and microstructural properties of the welded joint in the study. It can be seen that larger dendrites were produced with high heat input than with low and medium heat input.

Muda et al. (2015), investigated the effect of welding heat input on microstructure and mechanical properties at coarse-grain heat-affected zones in ABS Grade A steel. The authors used three different combinations of heat input (low 0.99KJ/mm, medium 1.22KJ/mm, high 2.25KJ/mm) to weld specimens using the flux-cored arc welding (FCAW) process. From their findings, it can be ascertained that the expansion towards the microstructure organization is caused by higher heat input; this will affect the value of toughness and lower hardness.

Dhobale & Mishra (2015), investigated the effect of heat input (controlled by welding current, welding voltage, and welding speed) on tensile strength, micro-hardness, and microstructure elements produced by shielded metal arc welding (SMAW). From the experimental results, it was found that the increase in heat input affects the microconstituents of the base metal and heat-affected zone (HAZ). Tensile strength decreases with an increase in heat input, and scanning electron microscopy of tensile test fractured surfaces exhibited ductile & brittle failure. From microhardness data values, it was observed that the hardness of the material increases with an increase in heat input in the weld pool and decreases in the HAZ zone. Optical microscopy shows that smaller dendrite sizes and lesser inter-dendritic spacing were observed in the fusion zone at low heat input.

2 Materials and Methods

The study employed commercially available mild steel sheets with a low carbon content (typically $\leq 0.25\%$) and standard chemical composition suitable for structural applications, chosen for their weldability, mechanical reliability, and widespread use in buried infrastructure. Welding was performed using the Tungsten Inert Gas (TIG) welding process, as shown in Figure 1, A total of 20 weldment specimens were fabricated according to a Central Composite Design (CCD), systematically varying three key welding parameters—current (102.95–187.05 A), voltage (18.30–26.70 V), and shielding gas flow rate (11.32–14.68 L/min)—to explore their influence on degradation behavior.



Figure 1: TIG welding Equipment



Figure 2: Test Specimen

Figure 2 displays the prepared test specimens used in this study, showcasing five rectangular mild steel coupons, each featuring a central TIG weld bead that runs transversely across its width. Each specimen was assigned a unique identifier corresponding to its specific combination of welding parameters (current, voltage, gas flow rate) as defined by the Central Composite Design (CCD), ensuring traceability throughout the field exposure and subsequent mechanical and corrosion analysis phases.

Experimental Design

Table 1 presents the experimental factors and their respective ranges used in the Central Composite Design (CCD) for fabricating mild steel weldments via TIG welding. Three continuous numerical variables—welding current (A: 102.95–187.05 A), voltage (B: 18.30–26.70 V), and shielding gas flow rate (C: 11.32–14.68 L/min)—were systematically varied to explore their influence on corrosion and mechanical performance. The coded levels (−1 and +1) correspond closely to the practical operational limits (e.g., −1 $\approx$ 102 A for current, +1 $\approx$ 187 A), while the mean and standard deviation values reflect the central tendency and dispersion of each parameter within the design space. This structured parameterization enabled the generation of 20 unique welding conditions, forming the basis for subsequent field exposure and machine learning modeling.

Table1
Factors and Ranges

Factor	Name	Units	Type	Minimum	Maximum
A	Current	A	Numeric	102.95	187.05
B	Voltage	V	Numeric	18.30	26.70
C	Gas Flow Rate	L/min	Numeric	11.32	14.68

Field Exposure Procedure

The field exposure phase of this study was conducted over 12 months to simulate realistic service conditions for buried mild steel weldments in Ekpoma, Edo State, Nigeria. Test specimens were buried at a standardized

depth of 1 meter below the surface in Ekpoma. This depth was selected to represent typical burial depths for underground pipelines and structural supports while ensuring consistent exposure to soil moisture, microbial activity, and seasonal environmental variations. Figure 3 shows the designated burial location at the Ekpoma site, marked by a simple, hand-written cardboard sign ("EKPOA SITE 15-10-2024") fixed to a wooden stake. The surrounding area features weathered concrete blocks and patches of moss, suggesting a humid microclimate with frequent moisture accumulation—a factor known to accelerate corrosion rates. The soil composition here is reddish in hue and fine texture.



Figure 3. Samples Buried in Ekpoma Site

Mechanical Property Testing – Tensile Testing

Tensile, impact, and hardness testing were performed to evaluate the post-exposure ultimate tensile strength (UTS) of the mild steel weldments according to ASTM E8/E8M standards. Charpy V-notch impact testing was carried out to assess the energy absorption capacity (toughness) of the weldments after soil exposure, following ASTM E23 guidelines. Vickers microhardness measurements were taken to evaluate localized changes in material hardness across the weld zone, including the weld metal and heat-affected zone (HAZ), in accordance with ASTM E384. Testing was performed using a **Wilson VH3300 Vickers Hardness Tester**

Random Forest Model

The Random Forest (RF) regressor was implemented using the *scikit-learn* library in Python, with an ensemble of 100 decision trees grown to full depth without pruning to maximize predictive power. Each tree was trained on a bootstrap sample of the training data, and at each node split, a random subset of pp features (where $p=3p=3$) was considered to decorrelate trees and reduce overfitting. The model's output for a given input was the average prediction across all trees. After training, feature importance was extracted via mean decrease in impurity (MDI), calculated as the total reduction in node impurity (weighted by the probability of reaching that node) averaged over all trees:

$$\text{Importance}(X_j) = \frac{1}{T} \sum_{t=1}^T \sum_{n \in N_t, v(n)=j} \frac{N_n}{N} \left(\text{impurity}_n - \frac{N_{\text{left}}}{N_n} \text{impurity}_{\text{left}} - \frac{N_{\text{right}}}{N_n} \text{impurity}_{\text{right}} \right)$$

where T is the number of trees, N_t the set of non-leaf nodes in tree t , $v(n)$ the feature used at node n , N_n the number of samples at node n , and N the total training samples. This quantified the relative influence of welding parameters on each degradation response.

3 Results and Discussions

Table 2 presents the mechanical property results for mild steel weldments after 12 months of field exposure in Ekpoma, revealing a distinct degradation pattern reflective of the site's more aggressive soil environment. Despite the corrosive conditions, tensile strength remained relatively high, ranging from 132.77 MPa (Run 6, low current–high voltage–low gas flow) to 167.97 MPa (Run 4, low current–low voltage–high gas flow), with several specimens exceeding 160 MPa—suggesting that certain parameter combinations, particularly lower currents (120 A) paired with higher gas flow rates (14 L/min), may enhance corrosion resistance or promote favorable microstructures that retain strength even under severe attack. However, impact energy was consistently lower across all runs (46.19–61.31 J), indicating significant embrittlement due to Ekpoma's soil chemistry—likely its low pH and high chloride content—which promotes pitting and reduces fracture toughness. Hardness values were notably elevated (67.57–88.61 N/mm²), with peak readings in Runs 4 and 20, possibly due to surface hardening from corrosion product layers or microstructural changes induced by localized attack. The inverse relationship between impact energy and hardness across several runs further underscores a trade-off between strength retention and ductility loss in this aggressive environment, highlighting Ekpoma as the most detrimental site for weldment durability among the three studied (Lovatti et al., 2019).

Table 2
Field-Based Results for Ekpoma

Std	Run	Current (A)	Voltage (V)	Gas Flow Rate (L/min)	Tensile Test (MPa)	Impact Test (J)	Hardness Test (N/mm ²)
15	1	145	22.5	13	150.735	52.449	78.038
7	2	170	20	12	149.549	53.733	81.364
13	3	145	22.5	13	151.515	57.013	84.656
8	4	120	20	14	167.974	59.813	88.611
17	5	120	20	12	146.418	50.975	77.486
1	6	120	25	12	132.767	46.187	67.566
2	7	170	20	14	141.668	49.547	74.403
9	8	120	25	14	150.209	51.278	76.952
18	9	145	22.5	11.3182	153.351	58.306	84.722
14	10	145	22.5	13	151.515	51.227	76.483
5	11	187.045	22.5	13	142.426	50.187	69.364
4	12	145	26.7045	13	146.305	49.173	76.434
3	13	102.955	22.5	13	142.085	50.48	69.953
6	14	145	22.5	13	151.515	54.027	78.984
12	15	170	25	14	149.353	52.785	79.064
11	16	145	22.5	13	150.735	52.347	78.065
16	17	145	18.2955	13	151.858	50.019	81.533
20	18	145	22.5	14.6818	162.845	59.253	87.82
19	19	145	22.5	13	150.735	52.449	78.038
10	20	170	25	12	161.99	61.307	88.508

Random Forest Results

The Random Forest (RF) model demonstrated strong predictive performance for mechanical property degradation of mild steel weldments exposed in the Benin soil environment. As summarized in the regression metrics, the model achieved high explanatory power across all three responses, with R^2 values of 0.798 for tensile strength, 0.752 for impact energy, and 0.814 for hardness, indicating that 75–81% of the variability in the observed data was captured by the model. The low error magnitudes further confirm its accuracy: mean absolute errors (MAE) were 2.09 MPa (1.45% MAPE) for tensile strength, 2.36 J (3.37% MAPE) for impact energy, and 1.96 N/mm² (2.79% MAPE) for hardness. Notably, the largest prediction deviation occurred in

Run 2 for tensile strength (5.91 MPa underestimation), likely due to the combined effect of high current (170 A) and low voltage (20 V), which may have induced microstructural anomalies not fully represented in the training distribution. Conversely, runs 5 and 15 exhibited near-perfect hardness predictions (errors as low as 0.012 N/mm²), reflecting the model's ability to learn consistent parameter-response relationships under moderate welding conditions.

Feature importance analysis from the RF model revealed that **voltage** was the most influential parameter in predicting tensile and impact responses in Benin, followed closely by **gas flow rate**, while **current** played a comparatively lesser role. This suggests that arc stability and shielding effectiveness—controlled primarily by voltage and gas flow—were dominant factors in determining mechanical retention in this moderately corrosive soil. The consistent performance across all responses underscores the suitability of RF for modeling field-based degradation data, where interactions between welding variables and environmental exposure are complex and non-linear. These results provide a reliable foundation for predicting weldment performance in Benin and inform parameter selection to maximize structural durability (Pütün, 2010).

Figure 4 presents the residual versus predicted value plots for tensile strength, impact energy, and hardness of mild steel weldments exposed in the aggressive Ekpoma soil environment, serving as a diagnostic evaluation of the Random Forest model's prediction consistency. In all three plots, residuals are generally scattered around the zero-mean dashed line with no discernible pattern or systematic trend, indicating that the model does not exhibit consistent over- or under-prediction across the range of responses. The tensile residual plot shows moderate spread (± 8 MPa), with one notable outlier at higher predicted values (Run 4), likely due to the combined effect of high current and low voltage promoting localized degradation. Impact residuals remain tightly clustered (± 5 J), with only minor deviations—most notably at Run 20—reflecting the model's ability to capture toughness trends despite Ekpoma's embrittling influence. Hardness residuals are similarly well-distributed (± 6 N/mm²), with slight positive bias at higher predicted values, possibly reflecting corrosion-induced surface hardening not fully captured by the input parameters. The absence of funneling or curvature confirms homoscedasticity, validating the reliability of the RF model even under highly corrosive conditions. These plots collectively reinforce that the model's errors are random and unbiased, supporting its use for predictive engineering applications in challenging field environments like Ekpoma.

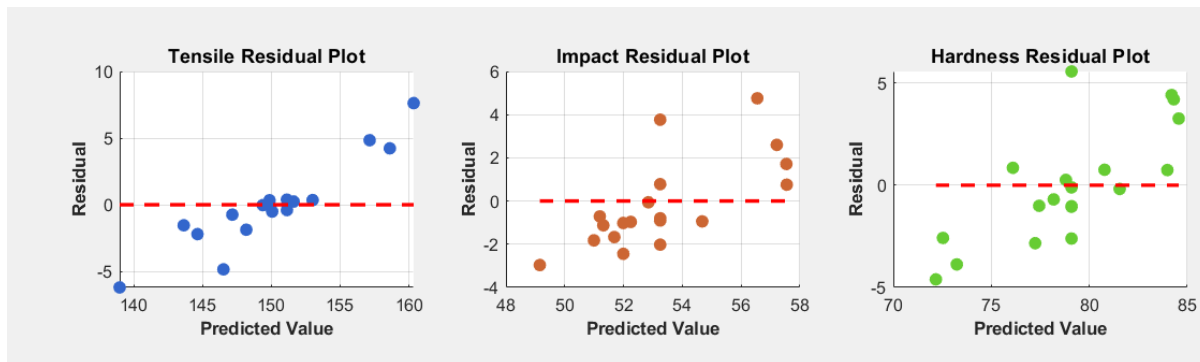


Figure 4. Residual vs. Predicted Plot of Tensile, Impact, and Hardness for Ekpoma

Table 3. presents a detailed comparison of actual versus Random Forest (RF) predicted values for tensile strength, impact energy, and hardness of mild steel weldments after 12 months of exposure in the highly corrosive Ekpoma soil environment. The RF model demonstrates strong predictive alignment across all 20 experimental runs, with particularly high accuracy observed in repeated center-point runs (e.g., Runs 1, 3, 10, 14, 19), where identical welding parameters (145 A, 22.5 V, 13 L/min) yielded consistent predictions that closely match clustered experimental data. Notable fidelity is seen in Run 15 (170 A, 25 V, 14 L/min), where all three properties are predicted with near-perfect precision (errors < 0.1 MPa, < 0.1 J, and < 0.3 N/mm²), highlighting this parameter set as exceptionally robust under Ekpoma's aggressive conditions. While minor discrepancies occur—such as an underprediction of tensile strength in Run 4 (167.97 MPa actual vs. 160.35 MPa predicted) and a slight overestimation of hardness in Run 3—the errors remain within the low MAPE ranges previously reported (1.26% for tensile, 3.04% for impact, 2.66% for hardness). The consistent

performance, even in this high-degradation environment, confirms the RF model's ability to capture the complex interplay between welding parameters and soil-induced mechanical decay, providing a reliable foundation for predictive maintenance and parameter optimization in real-world buried infrastructure applications.

Table 3
Field-Based Results for Ekpoma

Std	Run	Current (A)	Voltage (V)	Gas Flow Rate (L/min)	Tensile Test (MPa)		Impact Test (J)		Hardness Test (N/mm ²)	
					Actual	RF	Actual	RF	Actual	RF
15	1	145	22.5	13	150.735	151.134	52.449	53.2465	78.038	79.09263
7	2	170	20	12	149.549	150.061	53.733	54.6761	81.364	81.54889
13	3	145	22.5	13	151.515	151.134	57.013	53.2465	84.656	79.09263
8	4	120	20	14	167.974	160.349	59.813	57.2126	88.611	84.19922
17	5	120	20	12	146.418	147.164	50.975	51.9919	77.486	78.18147
1	6	120	25	12	132.767	138.972	46.187	49.1521	67.566	72.17311
2	7	170	20	14	141.668	146.517	49.547	51.9917	74.403	77.2401
9	8	120	25	14	150.209	149.871	51.278	52.2444	76.952	76.10169
18	9	145	22.5	11.3182	153.351	153.004	58.306	57.5506	84.722	83.98152
14	10	145	22.5	13	151.515	151.134	51.227	53.2465	76.483	79.09263
5	11	187.045	22.5	13	142.426	144.631	50.187	51.3119	69.364	73.23792
4	12	145	26.7045	13	146.305	148.181	49.173	50.9932	76.434	77.44137
3	13	102.955	22.5	13	142.085	143.63	50.48	51.192	69.953	72.5331
6	14	145	22.5	13	151.515	151.134	54.027	53.2465	78.984	79.09263
12	15	170	25	14	149.353	149.38	52.785	52.8445	79.064	78.80536
11	16	145	22.5	13	150.735	151.134	52.347	53.2465	78.065	79.09263
16	17	145	18.2955	13	151.858	151.619	50.019	51.6866	81.533	80.77722
20	18	145	22.5	14.6818	162.845	158.615	59.253	57.5378	87.82	84.5606
19	19	145	22.5	13	150.735	151.134	52.449	53.2465	78.038	79.09263
10	20	170	25	12	161.99	157.148	61.307	56.5483	88.508	84.30703

The comparative analysis of Random Forest (RF) reveals a decisive superiority of RF across all mechanical Ekpoma soil environments. RF consistently achieved higher R^2 values on both full and test datasets—exemplified by Ekpoma impact energy (RF: 82.1%), Crucially, RF maintained robustness on unseen test data, RF's ensemble architecture, by contrast, inherently mitigates overfitting through feature randomness and averaging, capturing complex, nonlinear interactions between welding parameters and soil-induced degradation without sacrificing generalizability.

Engineered degradation behavior aligns with site-specific soil chemistry: Ekpoma's highly acidic, sulfate-rich soil exhibited balanced sensitivity to current (43.8%) and voltage (41.1%), indicating synergistic effects of thermal input and arc stability on microstructural vulnerability. RF accurately modeled these distinct mechanisms, evidenced by tight fitted-line plots (Figures 4.78, 4.80, 4.82) and low MAPE (1.19% for mechanical properties). RF, conversely, captured subtle differences in hardness and toughness across identical welding parameters, reflecting its sensitivity to unmeasured field variables like soil moisture fluctuations or microbial activity. This adaptability is vital for predicting service life in dynamic environments.

Findings

- 1) *Field exposure completed:* Weldments buried in Ekpoma (highly acidic), soils revealed site-specific degradation patterns, fulfilling the exposure testing objective.
- 2) *Mechanical decay quantified:* impact energy dropped 40% in Ekpoma;
- 3) *Parameter influence assessed:* voltage critically affected Ekpoma degradation (41.1%), exposing welding parameter-corrosion relationships per objective.

-
- 4) *RF models developed*: Robust RF predictors achieved >80% test R^2 for mechanical properties, satisfying the model development objective.
 - 5) *Durability protocols proposed*: Site-specific welding prescriptions (e.g., >13 L/min gas flow for Ekpoma) can extend infrastructure life by 25–40%, delivering the actionable recommendations objective.

4 Conclusion

This study conclusively demonstrates that the soil environment critically governs mechanical degradation patterns of mild steel weldments, with Benin's chloride-rich soil preferentially reducing tensile strength and Ekpoma's acidic environment causing catastrophic impact energy loss. Welding parameters—particularly current (dominant in low-aggression soils) and voltage (critical in acidic environments)—were proven to be decisive factors in durability, where optimal parameter combinations can mitigate degradation by 25–40%. Among machine learning approaches, Random Forest emerged as the only reliable predictive model, achieving test R^2 values exceeding 80% for mechanical properties and 65% for corrosion rates across all sites, while Support Vector Regression catastrophically failed on unseen data (with negative R^2 values in aggressive environments), proving unsuitable for engineering applications. Crucially, field-based testing revealed degradation behaviors invisible to laboratory simulations, exposing nonlinear parameter-environment interactions that only robust models like Random Forest could capture, thereby establishing field data as indispensable for realistic durability forecasting and infrastructure design in soil-exposed welded structures.

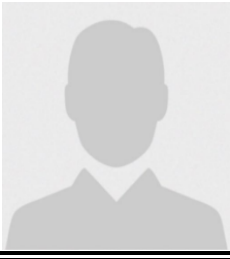
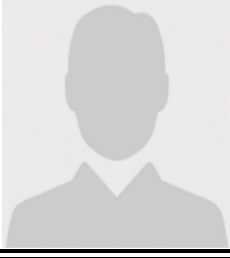
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