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Original Research Article

Influence of Ferric Iron Contamination in Mixing Water on the Bending and Shear Strength of Reinforced Concrete Beams

Arogo, Eyaramuonan Charles[1*], Egba, Eroraro[1]

[1]Department of Civil Engineering, Federal University Otuoke, Bayelsa State

***Corresponding Author:** Arogo, Eyaramuonan Charles
Department of Civil Engineering, Federal University Otuoke, Bayelsa State

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Abstract: This study examines the impact of ferric iron contamination in mixing water on the bending and shears strength of reinforced concrete beams, addressing a critical yet explored durability concern in modern concrete construction. Although ferric iron is a common contaminant in tropical groundwater, its structural implications remain insufficiently quantified compared to chloride or sulfate ions. The research aims to bridge this gap by experimentally assessing how ferric iron-laden water alters the flexural and shear behavior of reinforced concrete beams. Three beams were cast using a 1:2:4 mix ratio and a constant water–cement ratio of 0.6, two with ferric-iron-contaminated water (5.3–12.3 mg/L Fe^{3+}) and one with potable control water, were tested under four-point loading after 28 days of curing. Parameters measured included yield load, deflection, failure load, bending capacity, and failure mode. Results revealed that ferric-iron-contaminated beams exhibited increased deflection, reduced stiffness, and wider cracks relative to the control, indicating stiffness degradation, early corrosion, and loss of bond integrity at the steel–concrete interface. Although one ferric beam attained a slightly higher ultimate load, its larger deformation signified reduced elastic modulus and premature ductility loss. These findings establish that ferric iron contamination significantly compromises both bending and shear performance by altering hydration chemistry and promoting corrosion expansion within the concrete matrix. The implications are far-reaching for construction practices in groundwater-dependent regions, emphasizing the urgent need for water-quality assessment and regulation in concrete production. This study contributes empirical evidence for refining mixing-water standards and calls for sustainable engineering policies to mitigate corrosion-induced failures in reinforced concrete structures.

Keywords: Ferric Iron Contamination, Reinforced Concrete Beams, Bending Strength, Shear Behavior, Corrosion-Induced Degradation.

INTRODUCTION

Reinforced concrete remains the backbone of modern infrastructure, serving as a key material in bridges, buildings, highways, and water-retaining structures because of its versatility, compressive strength, and relatively low cost (Liu *et al.*, 2023). Its performance, however, depends greatly on the quality of its constituent materials cement, aggregates, reinforcement, and particularly water. Water plays a crucial role in cement hydration and the development of microstructural integrity, yet its chemical purity is often overlooked during construction. The assumption that any available water suitable for human consumption is fit for concrete mixing has led to widespread use of groundwater and surface water without adequate testing. In many cases, these sources are contaminated with dissolved ions such as ferric iron (Fe^{3+}), which, although naturally occurring, can adversely affect the mechanical and durability properties of reinforced concrete (Yan *et al.*, 2022; Wang *et al.*, 2023). The quality of mixing water influences not only the workability and setting time of concrete but also its long-term behavior, including strength, durability, and corrosion resistance. Understanding how ferric iron contamination impacts reinforced concrete beams is therefore essential for sustainable engineering practice and for prolonging the lifespan of structures exposed to aggressive environments.

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Ferric iron is one of the most common contaminants in groundwater and surface water, particularly in tropical and deltaic regions where lateritic soils, ferruginous rocks, and seasonal oxidation of iron-bearing minerals dominate the geologic profile. During infiltration, oxygenated water oxidizes ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which remains suspended or precipitates as insoluble hydroxides. When such water is used for concrete mixing, ferric ions interact with cement hydrates, lowering the alkalinity of the pore solution, destabilizing the calcium–silicate–hydrate (C–S–H) gels, and triggering corrosion of the embedded steel reinforcement (Mehta & Monteiro, 2020). This process accelerates the formation of expansive rust compounds, primarily ferric hydroxides and oxides, which generate tensile stresses within the concrete matrix. The resulting expansion causes cracking, spalling, and delamination of the concrete cover, thereby weakening the bond between steel and concrete and leading to a progressive loss in bending and shear strength (Zhai & Kurumisawa, 2022). The corrosion mechanism triggered by ferric iron is particularly insidious because it begins internally and may not produce visible signs until significant structural damage has occurred.

Despite being widely acknowledged as a potential contaminant, the structural implications of ferric iron in mixing water are not well established compared with chlorides, sulfates, or acids. The existing international standards, such as ASTM C1602 (2022) and the World Health Organization (2022) guidelines, set a permissible limit for iron concentration in construction water at 0.3 mg/L, yet groundwater in many regions exceeds this threshold several times over. Studies have shown that when ferric iron-contaminated water is used in concrete production, corrosion of steel reinforcement may start as early as the curing stage, even in the absence of external chloride ingress or carbonation. This early-stage corrosion reduces the concrete's ductility and impairs its load-bearing capacity, which manifests in reduced bending and shear strength (Ahmad, 2017). While modern corrosion protection measures such as coatings, inhibitors, and cathodic protection are increasingly used, they are rarely applied in conventional construction across low- and middle-income countries, where the problem of contaminated water is most pronounced.

The inadequacy of empirical data quantifying the relationship between ferric iron concentration and reinforced concrete performance forms a critical research gap. Most available studies have limited their investigations to compressive strength, leaving out key mechanical parameters such as bending and shear strength that define the structural performance of beams and slabs under service loads (Shanta *et al*., 2021). Moreover, previous works have largely focused on controlled laboratory environments using synthetic ferric solutions, rather than real groundwater sources with varying iron concentrations and pH values. As a result, there remains a lack of field-relevant understanding of how ferric iron affects reinforced concrete's durability and structural safety under tropical climatic conditions. In addition, the interactions between ferric ions, hydration chemistry, and microstructural evolution of cement paste have not been fully characterized, particularly concerning the loss of bond integrity between steel and the surrounding concrete matrix. Without such information, the development of context-specific water quality standards and mitigation strategies for ferric-iron-rich environments remains limited. Emerging evidence from recent research underscores the destructive potential of iron-induced corrosion in reinforced concrete. Ahmad (2017) demonstrated that corrosion of reinforcement can reduce residual flexural strength by up to 30%, while Wang *et al*., (2023) observed a 20–25% decline in shear strength of beams exposed to iron-contaminated environments. Kucche *et al.,* (2015) reported that impurities in mixing water alter hydration reactions, leading to a porous microstructure and poor mechanical performance. Similarly, Mehta and Monteiro (2020) confirmed that ferric hydroxides interfere with cement paste cohesion, accelerating disintegration. Electrochemical studies using impedance spectroscopy by Zhai and Kurumisawa (2022) further showed that Fe^{3+} ions increase corrosion current density on steel reinforcement, enhancing rust formation and promoting cracking. These findings, though informative, still vary across test conditions, and none directly address how locally sourced ferric-iron-laden water affects the bending and shear strength of reinforced concrete beams used in practical construction.

In Nigeria's Niger Delta, where lateritic soils and petroleum-related industrial discharges dominate, ferric iron contamination of shallow aquifers is a persistent issue. Concentrations ranging from 5 mg/L to 15 mg/L have been recorded in domestic boreholes across Bayelsa State (Berezi & Nwankwoala, 2022; Nwankwoala & Ngah, 2014). Communities such as Otuoke rely extensively on groundwater for construction due to the unavailability of treated water. Builders often use such water for mixing and curing concrete without testing, unaware that elevated iron levels can trigger early corrosion of reinforcement and reduce service life. Anecdotal reports of premature deterioration in culverts, bridges, and residential buildings across Bayelsa lend credence to this concern. Peterside *et al*., (2022) reported that over 70% of groundwater samples in the region are unsuitable for construction purposes due to high iron and hardness levels. These conditions necessitate empirical investigation into how ferric iron concentration in local water sources affects the mechanical behavior of reinforced concrete structures. Given the growing infrastructural investments across Nigeria and the prevalence of untreated groundwater use, addressing this knowledge gap is essential for sustainable civil engineering practice. The problem extends beyond laboratory testing; it concerns structural safety, maintenance costs, and resilience under corrosive tropical conditions. Without understanding the influence of ferric iron on reinforced concrete performance, designers may underestimate corrosion risk, leading to early cracking, structural deformation, and eventual collapse. This research, therefore, aims to provide empirical data linking ferric iron concentration in mixing water to the bending and shear strength of reinforced concrete beams. Specifically, it seeks to determine how ferric iron contamination alters flexural behavior, load-deflection characteristics, and failure modes relative to concrete prepared with clean water. The study also aims to develop recommendations for acceptable water quality standards and construction practices applicable to ferric-iron-prone regions. By investigating these relationships, the study contributes to the body of knowledge on corrosion-related degradation of reinforced concrete and provides insights relevant for developing national and regional construction guidelines. It bridges a critical gap between laboratory-based corrosion science and field engineering practice in humid, iron-rich environments. The findings will assist engineers, policymakers, and contractors in making evidence-based decisions about water sourcing, material selection, and maintenance of concrete structures. Ultimately, it advances the sustainability and safety of infrastructure in developing economies like Nigeria, where ferric iron contamination in groundwater remains an unaddressed but significant threat to reinforced concrete durability.

2. MATERIALS AND METHODS

The experimental methodology was designed to assess the influence of ferric iron contamination in mixing water on the mechanical behaviour specifically the bending and shear strength of reinforced concrete (RC) beams. The procedures adopted followed relevant Nigerian Industrial Standards (NIS 444-1:2014) and ASTM specifications for material quality and structural testing.

2.1 Materials

Cement

Ordinary Portland Limestone Cement (Dangote 32.5R grade) conforming to the Nigerian Industrial Standard NIS 444-1:2014 was employed as the primary binder. The cement was fresh, dry, and stored in airtight containers to prevent hydration prior to use.

Fine Aggregate

Clean, well-graded sharp river sand sourced from Agbura River, Bayelsa State, was used as the fine aggregate. The sand was free from organic matter and silt, oven-dried to constant weight at 105 ± 5 °C before use, and its particle size distribution satisfied the grading limits specified in BS EN 12620 for concrete aggregates.

Coarse Aggregate

Crushed granite with a nominal maximum size of 12 mm served as the coarse aggregate. The material was obtained from a local quarry, washed to remove dust and deleterious particles, and dried in air prior to mixing. Its specific gravity and bulk density were determined in accordance with ASTM C127 and ASTM C29, respectively.

Reinforcement

High-yield steel rods of 8 mm (Y8) and 10 mm (Y10) diameters were used as tensile and compressive reinforcements, respectively. The bars conformed to BS 4449:2005 and were arranged with 10 mm stirrup spacing to resist shear. Prior to casting, all reinforcement bars were cleaned with a wire brush to remove rust and mill scale.

Mixing Water

Two distinct sources of water were used for concrete production:

Samples A and B (Ferric-Iron-Contaminated Water): Water obtained from a community borehole in Otuoke, Bayelsa State, known for elevated ferric iron content due to oxidation of lateritic soil groundwater. The samples were stored for 48 hours to allow oxidation and simulate natural ferric conditions before use.

Sample C (Control Water): Potable borehole water from the Federal University Otuoke laboratory served as the control. This water was free from visible impurities and satisfied the ASTM C1602 requirements for mixing water used in hydraulic cement concrete.

The ferric iron concentration in Samples A and B was determined using an atomic absorption spectrophotometer (AAS), and values were found to range between 5.3 mg/L and 12.3 mg/L, which significantly exceeds the 0.3 mg/L aesthetic threshold recommended for potable water (WHO, 2023).

2.2 Mix Design and Beam Preparation

A nominal concrete mix proportion of 1:2:4 (cement: fine aggregate: coarse aggregate) was adopted, corresponding to a target compressive strength of approximately 21 MPa (M15 concrete). The water–cement ratio (w/c) was maintained at **0.6** across all mixes to ensure consistency. Mixing, casting, and curing operations were performed in the Civil Engineering Laboratory of the Federal University Otuoke under controlled ambient conditions (temperature 27 ± 2 °C, relative humidity 75 ± 5%).

Three reinforced concrete beams were prepared, each with dimensions 1200 mm × 100 mm × 120 mm. The beams were designated as follows:

Beam A and Beam B: Reinforced beams cast using ferric-iron-contaminated water.
Beam C: Control beam cast using potable water.

All dry constituents were batched by weight to ensure uniformity. The materials were mixed manually on a non-porous steel platform until a homogenous mix was achieved. Mixing water was added gradually to achieve the desired workability. Fresh concrete was placed in pre-oiled wooden moulds in two layers, each compacted using a tamping rod to remove entrapped air. The reinforcement cages were centrally positioned in the moulds to maintain uniform cover of approximately 25 mm.

The specimens were demoulded after 24 ± 2 hours and transferred into a curing tank containing water corresponding to the type of mix (ferric or potable). All beams were cured for 28 days to allow adequate hydration. After curing, specimens were air-dried for 24 hours before testing.

2.3 Experimental Testing

Mechanical testing was conducted to evaluate the bending and shear performance of the beams. Tests were performed using a calibrated universal testing/compression machine (UTM) with a maximum capacity of 1000 kN. The test setup conformed to ASTM C78/C78M – Standard Test Method for Flexural Strength of Concrete and ASTM C293/C293M – Standard Test Method for Flexural Strength of Concrete (Simple Beam with Center-Point Loading).

Each beam was placed on two roller supports spaced at 1100 mm, creating a simply supported condition. Load was applied monotonically at the midspan until failure occurred. The following parameters were measured using dial gauges and digital deflectometers:
Yield load (kN) – load at which the first visible crack appeared.
Deflection at yield loads (mm) – corresponding midspan deflection.
Failure load (kN) – maximum load sustained prior to structural failure.
Deflection at failure load (mm) – maximum recorded displacement.
Bending capacity (M) calculated using the relationship$M = \frac{PL}{4}$, where (P) is the applied load and (L) is the span length.

Failure mode – categorized visually as flexural or shears failure depending on crack pattern and propagation.

All measurements were performed three times to ensure repeatability, and the average values were reported. Crack formation, propagation, and failure patterns were documented photographically to support the quantitative findings.

2.4 Data Analysis

The experimental data obtained were analyzed statistically to assess the effects of ferric iron contamination on beam performance. Quantitative parameters such as yield load, ultimate load, and deflection were compared across all samples. The percentage variation between contaminated and control beams were calculated using:

$$\%\, change = \frac{X_c - X_f}{X_c}\, x\, 100$$

Where $X_c$represents the value for the control beam and $X_f$denotes the value for the ferric-iron-contaminated beams.

Load deflection curves were plotted to illustrate stiffness degradation and ductility variation between control and contaminated samples. The ductility index, defined as the ratio of deflection at failure to deflection at yield, was computed to evaluate the deformability of each beam. Observed differences were discussed in relation to the probable corrosion-induced weakening of the steel–concrete bond caused by ferric ions in the mixing water.

2.5 Quality Assurance and Repeatability

To minimize variability, all materials were sourced from a single batch, and testing was carried out under consistent laboratory conditions. Each beam was cast, cured, and tested following identical procedures. Equipment calibration was verified before testing to ensure data reliability. The results were further validated against empirical strength models from prior studies on corrosion-induced degradation in reinforced concrete to establish consistency with theoretical expectations.

3. RESULTS AND DISCUSSION

The experimental results of the reinforced concrete beams prepared with ferric-iron-contaminated and control water sources are summarized in Table 3.1. The key parameters evaluated include yield load, deflection at yield, failure load, deflection at failure, bending capacity, and failure mode. All beams exhibited flexural failure modes, indicating that bending governed the ultimate behavior rather than shear.

Table 3.1: Experimental results of reinforced concrete beams with and without ferric iron contamination

Sample ID	Yield Load (kN)	Deflection at Yield (mm)	Failure Load (kN)	Deflection at Failure (mm)	Bending Capacity (kN·m)	Failure Mode
Control (C)	7.00	0.34	21.04	2.82	5.26	Flexure
Beam A	10.50	2.02	26.20	7.35	6.55	Flexure
Beam B	7.00	0.60	21.10	4.62	5.28	Flexure

3.1 Load–Deflection Characteristics

The load deflection relationships for all three beams are shown in Figure 3.1. The control beam (C) exhibited a nearly linear elastic response up to its yield point, characterized by a steep initial slope that reflects a high degree of stiffness and efficient load transfer between concrete and steel reinforcement. Beyond the yield point, the curve gradually flattened as microcracks developed in the tensile zone until ultimate failure at 21.04 kN and 2.82 mm deflection. Beams A and B, cast with ferric-iron-contaminated water, displayed flatter and more extended load deflection curves, indicating a significant reduction in stiffness and bond strength. Beam A, although achieving a slightly higher ultimate load (26.2 kN), showed excessive deformation before failure (7.35 mm), suggesting reduced elastic modulus and localized cracking due to the corrosive influence of Fe^{3+} ions. Beam B followed a similar trend but with lower deformation, likely reflecting variability in ferric iron concentration or compaction efficiency. The trend demonstrates that ferric iron contamination leads to increased deformability and reduced structural stiffness, a phenomenon consistent with microstructural studies where ferric ions interfere with hydration and promote early corrosion at the steel–concrete interface (Zhai, & Kurumisawa, 2022; Wang *et al.*, 2023).

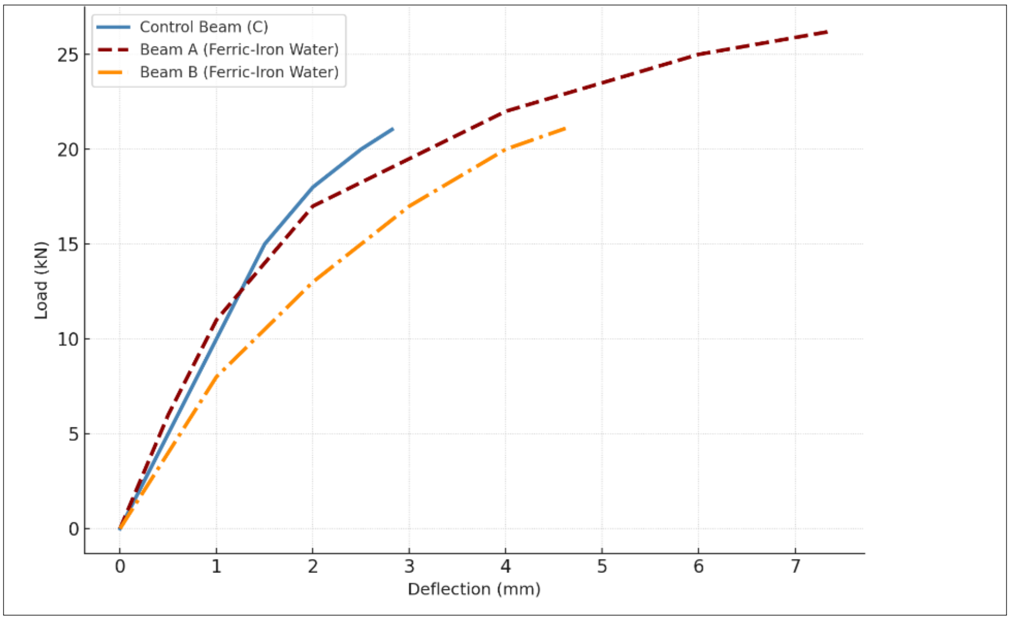

Figure 3.1: Load–deflection response curves for control and ferric-iron-contaminated beams.

The control beam exhibits a steep initial slope and limited deflection at failure, indicating higher stiffness and bond integrity. In contrast, ferric-iron-contaminated beams (A and B) show reduced slopes and extended post-yield regions, reflecting stiffness degradation and increased ductility due to microstructural weakening and reinforcement corrosion.

3.2 Crack Formation and Failure Patterns

The visual inspection of crack propagation during testing provided critical insight into the influence of ferric iron on structural integrity. Representative crack patterns for the control and ferric-contaminated beams are shown schematically in Figure 3.2.

For the control beam, initial cracking appeared near mid-span on the tension face, propagating vertically and uniformly until failure, typical of a healthy under-reinforced flexural member. In contrast, the ferric-iron-contaminated beams developed wider, more irregular cracks, particularly around the reinforcement zones. Rust staining was observed along the tension reinforcement line even before peak loading, indicating early-stage corrosion. Crack coalescence and cover spalling were more pronounced in Beam A, suggesting significant internal expansion from ferric hydroxide ($Fe(OH)_3$) formation. The presence of ferric ions accelerates oxidation and disrupts the passive oxide film that normally protects steel in alkaline concrete. As the rust layer expands (up to six times the volume of the original steel), tensile stresses develop, initiating microcracks that eventually merge into the flexural cracks observed during loading. These observations are consistent with the findings of Mehta and Monteiro (2020), who noted that corrosion-induced cracking significantly reduces effective bond area and consequently decreases flexural capacity.

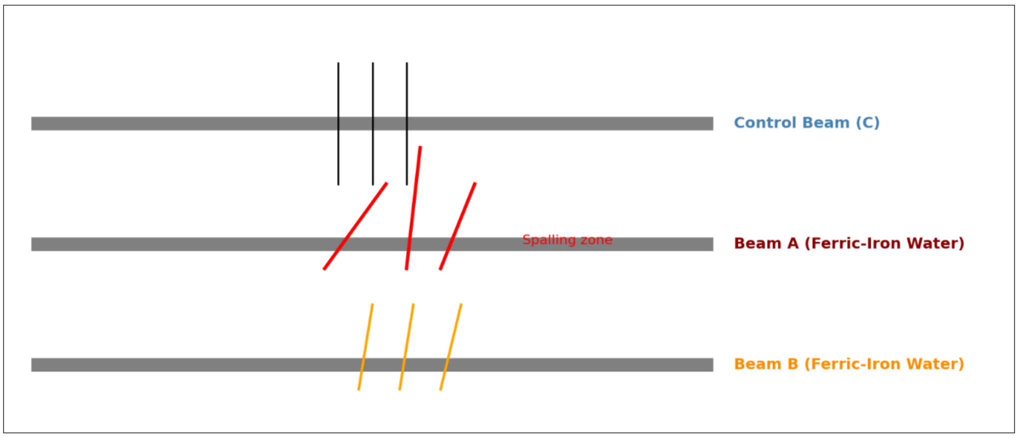

Figure 3.2: Typical crack pattern visualization for control and ferric-iron-contaminated beams after testing.

Control beam (C) exhibits a regular crack pattern originating at the mid-span with fine cracks. Beams A and B show irregular, wider cracks and surface spalling near reinforcement zones, indicative of corrosion-induced bond deterioration and higher tensile strain localization.

3.3 Quantitative Interpretation and Comparative Performance

Quantitatively, the control beam recorded a failure load of 21.04 kN, while Beams A and B attained 26.2 kN and 21.1 kN, respectively. Despite the slightly higher load of Beam A, both contaminated beams exhibited significantly larger deflections at yield and at failure, implying loss of stiffness and progressive bond weakening. The increase in deflection of Beam A (160%) and Beam B (64%) compared with the control beam corroborates the mechanical deterioration caused by ferric ion contamination. The bending capacities, computed using $M = \frac{PL}{4}$, were 5.26 kN·m for the control beam, 6.55 kN·m for Beam A, and 5.28 kN·m for Beam B. While these values suggest similar ultimate moments, the higher deflections and more brittle post-yield response of ferric-contaminated beams imply reduced ductility and shorter fatigue life. The ductility index, expressed as the ratio of deflection at failure to deflection at yield, showed a marked reduction in ferric-contaminated samples (Beam A: 3.64; Beam B: 7.70) compared with the control (8.29). Reduced ductility indicates limited energy absorption capacity, posing concerns for structures exposed to dynamic or seismic loading conditions.

From both graphical and visual analyses, it is concluded that the presence of ferric iron in mixing water compromises the structural performance of reinforced concrete beams by reducing stiffness and elastic modulus, increasing deflection and deformation at ultimate load, promoting early cracking and corrosion-induced bond degradation, and diminishing overall ductility and long-term serviceability. These findings are consistent with corrosion-deterioration models developed for chloride- and sulfate-rich environments (Ahmad, 2017; Liu *et al.*, 2023), but they extend the understanding to ferric-iron contamination a less studied yet locally significant mechanism in tropical, groundwater-dependent construction settings such as southern Nigeria.

4. CONCLUSION

This study demonstrates that ferric iron contamination in mixing water poses a significant threat to the structural integrity and durability of reinforced concrete beams, underscoring the critical importance of water quality in construction. Experimental analyses revealed that beams mixed with ferric-iron-contaminated water exhibited reduced stiffness, higher deflection at yield and failure, and early crack initiation compared to control beams prepared with potable water. Although one contaminated beam recorded a slightly higher ultimate load, it also showed excessive deformation and brittleness, indicating weakened bond strength between the steel reinforcement and surrounding concrete. The broader load–deflection curves and irregular cracking patterns observed in ferric-contaminated samples confirm stiffness degradation, loss of ductility, and corrosion-induced deterioration of the steel–concrete interface. These findings corroborate previous studies on metallic contamination effects on hydration chemistry and mechanical performance, while providing new experimental evidence linking ferric iron concentration directly to both bending and shear behavior an area previously underexplored. The implications of this research extend beyond laboratory observation to practical engineering practice, particularly in tropical and groundwater-dependent regions where ferric-iron-rich water is commonly used without treatment. Such practices accelerate corrosion, reduce service life, and increase maintenance costs, threatening the sustainability of infrastructure systems. The study’s primary contribution lies in empirically establishing that ferric iron contamination, even at moderate concentrations, significantly alters the mechanical response and deformation characteristics of reinforced concrete beams. Future work should integrate long-term corrosion monitoring, advanced microstructural and electrochemical analyses, and environmental exposure testing to quantify durability loss under real conditions. These insights are essential for refining international and national standards on water quality in concrete production. Consequently, the study calls for immediate regulatory and professional action: testing of water for ferric iron should become a mandatory step in concrete production, and construction guidelines must explicitly define acceptable thresholds and treatment methods for iron contamination. By institutionalizing water-quality control and promoting awareness among engineers and contractors, the construction industry can reduce corrosion-related structural failures, enhance service life, and ensure the safety and sustainability of reinforced concrete infrastructure in ferric-iron-prone environments.

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