

Corrosion Assessment of Reinforced Concrete Made with Secondary Treated Wastewater and Fly Ash, with Sodium Nitrite as a Corrosion Inhibitor

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Abstract - The corrosion of steel reinforcement in concrete, often caused by carbonation and chloride ingress, poses a significant threat to the durability of reinforced concrete structures. The use of secondary treated wastewater (STW) in concrete has emerged as a sustainable alternative to potable water, though its residual contaminants—such as chlorides and dissolved solids—raise concerns about increased corrosion risk. This study investigates the corrosion behavior of M30-grade concrete made with STW, incorporating 10% fly ash as a partial cement replacement and sodium nitrite at 1%, 2%, and 3% (by cement weight) as a corrosion inhibitor. Using the half-cell potentiometer method in accordance with ASTM C876-15, corrosion activity was monitored over 14 months. Concrete specimens with 50 mm and 100 mm cover depths were prepared using STW from three Bangalore treatment plants: Bellandur, Jakkur, and Nagasandra. Results revealed that sodium nitrite, particularly at 1% and 2%, significantly reduced corrosion risk, with half-cell potentials remaining above -200 mV—indicating a low probability of corrosion. A 100 mm cover depth provided better protection than 50 mm. Despite initial corrosion susceptibility due to STW contaminants, the use of fly ash and inhibitors effectively mitigated the risk. By the end of the study, corrosion performance was comparable to concrete made with potable water, supporting STW's feasibility in sustainable construction

Keywords: Secondary treated wastewater, Sodium nitrite, Fly ash, Durability, Half-cell potentiometer, reinforced concrete corrosion.

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1. Introduction

Concrete production is highly dependent on both water and cement, leading to considerable environmental implications. Annually, the industry uses approximately 2.5 tons of cement and about 1 billion tons of water for every cubic meter of concrete produced [1]. Typically, 150 to 210 liters of water are required to prepare one cubic meter of concrete. In 1997, the global concrete industry consumed more than 800 billion liters of water, with projections indicating a rise to 900 billion liters by 2030 [2,3]. This growing demand exerts immense pressure on the already scarce freshwater resources, particularly in rapidly urbanizing regions. Water quality is a critical factor in concrete performance. While treated wastewater presents a promising alternative to potable water, it often contains organic and inorganic substances that may interfere with cement hydration [4,5,6]. These contaminants can prolong

setting times and impair both the fresh and hardened properties of concrete. Therefore, maintaining high water quality is essential for reliable concrete production. One sustainable solution is the use of secondary treated wastewater (STW), or treated effluent, from municipal wastewater treatment plants. Domestic wastewater—originating from households, commercial buildings, and institutions—is collected through sewer networks and treated before being reused [7,8]. Treated effluent is already utilized in applications such as irrigation, industrial processes, and landscaping. In India, the use of treated wastewater in concrete is regulated by several agencies, including the Central Pollution Control Board (CPCB), Bureau of Indian Standards (BIS), State Pollution Control Boards (SPCBs), and local municipal authorities. International organizations, such as the Occupational Safety and Health Administration (OSHA) in the U.S., the Health and Safety Executive (HSE) in the U.K., and the International Labour Organization (ILO), provide additional guidance on health and safety considerations [9,10]. Furthermore, technical standards from institutions like the American Concrete Institute (ACI) offer recommendations for integrating effluent in concrete production [11]. To ensure responsible use of treated wastewater in construction, regulatory oversight by entities such as the Bangalore Water Supply and Sewerage Board (BWSSB)—which manages water supply and wastewater in Bengaluru—is crucial, especially for ready-mix concrete (RMC) operations..

The corrosion of steel reinforcement in concrete is a major concern affecting the durability, safety, and lifespan of reinforced concrete structures. Reinforced concrete effectively combines the compressive strength of concrete with the tensile strength of steel, but the structural integrity can be compromised when the embedded steel begins to corrode. This deterioration typically occurs when the concrete's naturally protective alkaline environment is disrupted, allowing aggressive agents such as moisture, oxygen, and chloride ions to reach the steel surface [12,13]. Common initiators include carbonation—where carbon dioxide reacts with the concrete—and chloride penetration from de-icing salts or marine exposure. As steel corrodes, it forms rust, which expands in volume and induces internal pressure, leading to cracking and spalling of the concrete cover. The durability of reinforced concrete depends heavily on the quality of materials used, including mixing water [14]. In response to environmental concerns and increasing water scarcity, the use of secondary treated

wastewater (STW) as a substitute for potable water in concrete production has emerged as a sustainable alternative. However, STW may contain residual chlorides, sulfates, inorganic salts, and organic compounds that can disrupt the electrochemical conditions protecting the steel, thereby accelerating the corrosion process [15]. These contaminants can break down the passive oxide film on the steel, promoting further degradation. Understanding the influence of treated wastewater on both concrete properties and reinforcement corrosion is crucial for developing durable and resilient structures. This discussion lays the foundation for evaluating the practical implications and challenges of using secondary treated wastewater in concrete, while exploring methods to mitigate corrosion and enhance long-term sustainability [16,17,18].

The half-cell potentiometer is a widely accepted non-destructive technique used to evaluate corrosion activity in reinforced concrete structures. It operates on electrochemical principles, measuring the electrical potential difference between a reference electrode—commonly copper-copper sulfate or silver-silver chloride—and the embedded steel reinforcement [19,20]. These potential differences reflect the likelihood and extent of corrosion, with more negative values typically indicating active corrosion, while less negative or stable readings suggest passive steel conditions [21,22]. This method is especially useful for identifying corrosion-prone zones, evaluating the severity of deterioration, and guiding maintenance or repair decisions. Its relevance increases in structures exposed to harsh environmental conditions or built using unconventional materials, such as secondary treated wastewater. In this study, the half-cell potentiometer method was employed to assess the corrosion risk associated with different concrete mixes incorporating treated wastewater, fly ash, and varying levels of sodium nitrite as a corrosion inhibitor [23,24]. By analyzing the electrochemical potential readings in conjunction with variables such as water quality, admixture concentration, and cement replacement, the study offers valuable insights into the practicality and performance of using treated wastewater in reinforced concrete applications [25].

Concrete was produced using a mix design that included 10% fly ash as a partial replacement for cement, along with sodium nitrite—an accelerating admixture—added in varying dosages of 1%, 2%, and 3% by weight of cement. As a sustainable alternative to freshwater, secondary treated wastewater (STW) sourced from

three different municipal treatment plants was utilized as the mixing water. This environmentally conscious approach aimed to assess the viability of using treated wastewater in concrete production while enhancing the material's properties through the combined effects of fly ash and chemical admixtures. The primary objective of the study was to investigate the corrosion behavior of steel reinforcement embedded in concrete made with STW. This is particularly critical, as reinforcement corrosion is a major durability concern, especially when alternative water sources—potentially containing residual salts or reactive compounds—are used, which may alter the electrochemical environment and compromise the stability of the embedded steel.

2. Half Cell Potentiometer

Exposure to elements such as carbon dioxide (CO_2) or chlorides can initiate corrosion, potentially compromising the concrete and reaching the steel reinforcement embedded within. Utilizing an accurate and dependable technique to evaluate corrosion is essential, as it plays a critical role in ensuring the structure's longevity and structural integrity. The Half-Cell Potential test, governed by standards ASTM C876-15 and IS-516, is widely acknowledged as a fundamental method for detecting and monitoring corrosion activity. Fig 1 depicts the configuration and working of a Half-Cell Potentiometer employed for this assessment.

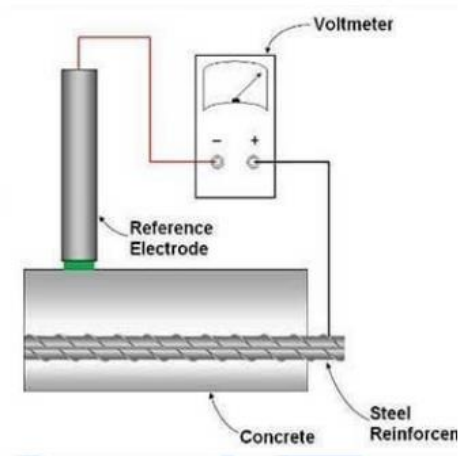


Figure 1. Assembly and Working of Half-cell potentiometer

2. 1. Half Cell Electrode Specification:

The half-cell electrode is a critical component in electrochemical measurements, particularly in corrosion studies of reinforced concrete. It typically consists of a reference electrode, such as a copper/copper sulfate (Cu/CuSO_4), silver/silver chloride (Ag/AgCl), or saturated calomel electrode (SCE), housed in a stable, durable casing. The electrode's primary function is to provide a consistent and stable potential against which the potential of the embedded steel can be measured. Key specifications (Table 1) include a well-defined reference potential, high ionic conductivity of the filling solution, and compatibility with the environment it will be used in (e.g., chloride-rich environments in concrete). Proper calibration and maintenance are essential to ensure accurate and reliable measurements. Fig 1 shows the working of Half-cell Potentiometer.

Specification: 1. Range: -999mV to $+999\text{mV}$, 2. Accuracy: $\pm 5\text{mV}$, 3. Power supply: Pencil Cell Battery and 4. Operating Temperature: 0° to -50°C .

Table 1. Parameters and requirements for a half-cell potentiometer

Parameters	Requirement as per IS516(4.2) clause	Equipment Specification
Inside diameter of Half-Cell electrode	25 mm	25 mm
Porous Plug Diameter	Not less than 13 mm	24 mm
Copper Rod diameter	6 mm	6 mm
Copper Rod length	Not less than 50 mm	95 mm
Measured Voltage across reference electrode	Not more than 0.0001 V	0.0000 V

3. Experimental Methods and materials

3. 1. Materials

This study utilized Grade 43 cement, which complies with IS: 12269 standards, having an initial setting time of 40 minutes and a final setting time of 330 minutes. Fine and coarse aggregates, procured from granite quarries in Karnataka, India, were used in the mix. The fine aggregate had a specific gravity of 2.82, a bulk density of 1.675 kg/m³, and a water absorption rate of 0.60%, while the coarse aggregate exhibited a specific gravity of 2.65, a bulk density of 1.780 kg/m³, and a water absorption rate of 0.15%. Powdered Class F fly ash was obtained from Karnataka Power Corporation Limited (KPCL) and was characterized by a specific gravity of 2.30, a pH of 11.6, electrical conductivity of 730 mS/cm, and a total solids content of 450 mg/L. To accelerate the setting process, sodium nitrite was incorporated in amounts ranging from 1% to 3% of the cement's weight.

3. 1.1. Secondary treated wastewater

To evaluate the potential of secondary treated wastewater for concrete production in alignment with IS 456 guidelines, samples were carefully collected from three wastewater treatment plants in Bangalore, utilizing distinct treatment technologies. The selected facilities Bellandur, Jakkur, and Nagasandra were chosen based on their recent commissioning in 2017 to 2018,

their strategic locations on the city's outskirts representing unique drainage zones, and the diversity of treatment processes employed. The table provides detailed information about three wastewater treatment plants located in Bangalore, highlighting their names, treatment processes, and corresponding drainage zones. The Bellandur plant, with a capacity of 90 Million Liters per Day (MLD), utilizes the **Activated Sludge Process** and is situated in the K & C Valley drainage zone. The Jakkur plant, with a smaller capacity of 15 MLD, employs the **Moving Bed Biofilm Reactor** (MBBR) and serves the Hebbal Valley drainage zone. Lastly, the Nagasandra plant, with a capacity of 20 MLD, uses the **Sequential Batch Reactor** (SBR) method and operates in the Vrushabhavati Valley drainage zone. Each plant adopts a unique wastewater treatment technology tailored to its specific requirements, with capacities ranging from 15 to 90 MLD, and they collectively contribute to the effective management of wastewater in Bangalore. These varied methodologies provide a holistic understanding of the quality and characteristics of treated wastewater across Bangalore. Table 2 outlines the chemical properties of tap water and secondary treated wastewater utilized in concrete manufacturing.

Table 2. The chemical properties of tap water and secondary treated wastewater

Sl. No.	Test	Name of wastewater treatment plants			Tap Water
		Bellandur	Jakkur	Nagasandra	
1	B.O.D (mg/l)	6.8	4.9	7.6	Nil
2	C.O.D (mg/l)	34	24	40	Nil
3	T.S.S. (mg/l)	9.2	3	15	6
4	Total Dissolved solids (mg/l)	530	682	770	214
5	Chlorides (mg/l)	141	172	184	37.99
6	Turbidity (NTU)	1.2	0.8	1.8	0.8
7	pH	7.36	7.18	7.3	7.5
8	Conductivity (ms/cm)	836	1085	1232	325

3.2 Experimental method

3.2.1 Design proportions of the various concrete mixes

The experimental study focused on the formulation, evaluation, and analysis of sixteen concrete mixtures incorporating four different water types (tap water and three varieties of secondary treated wastewater) along with 10% fly ash and varying sodium nitrite concentrations (1%, 2%, and 3%). The mix designs adhered to IS:10262 standards for M30 grade concrete. The required proportions of cement, coarse aggregate, fine aggregate, fly ash (10%), and sodium nitrite (1%, 2%, or 3%) were dry mixed to achieve uniformity before introducing the designated water type to prepare wet mixes, as detailed in Table 3. The concrete was prepared according to the specified design mix,

ensuring thorough mixing until a uniform consistency and colour were achieved. Mixing time in the mechanical mixer was maintained between 3 and 4 minutes. Immediately after mixing, the concrete was placed into cube molds. The fresh concrete was compacted either manually, following standard procedures, or using a vibrating table. During cube preparation, a steel rod of 150 mm length (10 mm diameter) was embedded with a 25 mm projection above the cube's surface. The compacted molds were stored at a controlled temperature of $27 \pm 2^\circ\text{C}$ and a relative humidity of at least 90% for 24 hours. After curing for 24 hours, the cubes with embedded steel rods were removed from the molds and submerged in the respective secondary treated wastewater (Jakkur, Nagasandra, and Bellandur), with the protruding steel exposed to the atmosphere to simulate real-world conditions.

Table 3. Mix design of the present study

Mix	Cement (kg/m ³)	Fly ash (kg/m ³)	Coarse aggregate (kg/m ³)	Fine aggregate (kg/m ³)	Sodium Nitrite (kg/m ³)	Water (kg/m ³)	Type of Water
Portable Water	410.0	0.0	1069.3	650.0	0.0	216.5	Tap Water
B-FA-0	410.0	0.0	1069.3	650.0	0.0	216.5	STW from Bellandur treatment plant
B-FA-10	369.0	41.0	1069.3	650.0	0.0	216.5	
B-FA-10+1%SN	369.0	41.0	1069.3	650.0	3.7	216.5	
B-FA-10+2%SN	369.0	41.0	1069.3	650.0	7.4	216.5	
B-FA-10+3%SN	369.0	41.0	1069.3	650.0	11.1	216.5	
J-FA-0	410.0	0.0	1069.3	650.0	0.0	216.5	STW from Jakkur treatment plant
J-FA-10	369.0	41.0	1069.3	650.0	0.0	216.5	
J-FA-10+1%SN	369.0	41.0	1069.3	650.0	3.7	216.5	
J-FA-10+2%SN	369.0	41.0	1069.3	650.0	7.4	216.5	
J-FA-10+3%SN	369.0	41.0	1069.3	650.0	11.1	216.5	
N-FA-0	410.0	0.0	1069.3	650.0	0.0	216.5	

N-FA-10	369.0	41.0	1069.3	650.0	0.0	216.5	STW from Nagasandra treatment plant
N-FA-10+1%SN	369.0	41.0	1069.3	650.0	3.7	216.5	
N-FA-10+2%SN	369.0	41.0	1069.3	650.0	7.4	216.5	
N-FA-10+3%SN	369.0	41.0	1069.3	650.0	11.1	216.5	

3. 2.2 Test Procedure of Half-cell potentiometer:

- First clean the copper rod, the rod may be cleaned by wiping it with a dilute solution of hydrochloric acid or simple water then wipe it with clean cloth.
- Then pour the Copper Sulphate solution in Half-cell tube, proportion of the solution should be as mentioned in IS516 and shake the solution properly.
- After shaking, keep it in vertical position with porous plug down side for 30-45 minutes so that the solution should penetrate through porous plug.
- Make a connection between Half-cell tube and reinforcing steel by the means of crocodile clip, as shown in the pictures above.
- In certain cases, this technique may require removal of some concrete to expose the reinforcing steel.
- Then do the connections as mentioned above.
- And keep the porous plug (Half-cell electrode) on concrete surface and make sure that the surface where the porous pot were kept should be wetted from simple soap solution.
- And note the reading, then compare with standard IS516 as shown in below Table 4.

Table 4. Result Interpretation

Half-cell potential reading vs. Cu/CuSO ₄	Probability of Steel Corrosion Activity
More positive than - 200 mV	90% probability of no corrosion
Between -200 and - 350 mV	An increased probability of corrosion
More negative than - 350 mV	90% probability of corrosion

4. Result and discussion

The half-cell potentiometer test results provided valuable insights into the corrosion potential of steel reinforcement in concrete made with secondary treated wastewater, incorporating 10% fly ash as a partial cement replacement and varying sodium nitrite (1%, 2%, and 3% by cement weight) as an accelerating admixture. The electrochemical potentials measured indicated variations in corrosion activity across the samples.

4.1 Nagasandra STP:

Figures 2 and 3 present the results of half-cell potential (E_{corr}) measurements for steel reinforcement in concrete made with secondary treated wastewater (STW), incorporating 10% fly ash and varying dosages of sodium nitrite (1%, 2%, and 3% by cement weight). These measurements were taken at two concrete cover depths (50 mm and 100 mm) over a period of 35 to 420 days, with performance compared to a control mix prepared using potable water and no corrosion inhibitor. At 59 days, the control mix registered half-cell potentials averaging around -270 mV, placing it within the “uncertain probability” range for corrosion risk as per

ASTM C876-15, which classifies values between -200 mV and -350 mV as indicating a moderate probability (10–90%) of active corrosion. In contrast, concrete samples treated with sodium nitrite showed significantly more positive potentials: the 1% and 2% dosages yielded readings near -150 mV, while the 3% dosage approached -130 mV, all indicating a <10% probability of corrosion initiation. As the exposure period extended to 180 days, E_{corr} values for the sodium nitrite-treated specimens further improved. The 3% sodium nitrite mix showed potentials nearing -75 mV, while the 1% and 2% mixes stabilized between -100 mV and -120 mV. At 420 days (14 months), the trend continued: the 3% dosage consistently maintained values around -50 mV, firmly in the “safe” zone (>-200 mV), which indicates a high likelihood of passivated, non-corroding steel. Meanwhile, the control specimen’s E_{corr} values plateaued around -200 mV, fluctuating slightly but never improving beyond the threshold of corrosion uncertainty. These readings suggest the control remained vulnerable to corrosion throughout the testing period. Concrete cover depth also influenced the results.

For all mixes, the 100 mm cover provided enhanced protection, with half-cell potentials more positive by 10–20 mV on average compared to their 50 mm counterparts. This further illustrates the protective benefit of increased concrete cover in conjunction with corrosion inhibitors. Interestingly, The 2% sodium nitrite dosage consistently outperformed 1% and 3% in mitigating corrosion across both 50 mm and 100 mm concrete cover depths. At 180 days, it showed up to 25 mV more positive half-cell potentials than the 1% mix and 15 mV more than the 3% mix, indicating lower corrosion probability. At 420 days, it maintained stable readings around -55 mV (100 mm cover), outperforming other dosages. While the 3% dosage was also effective, the 2% mix offered the best balance of early and long-term protection, making it the most efficient and practical choice for STW-based reinforced concrete.

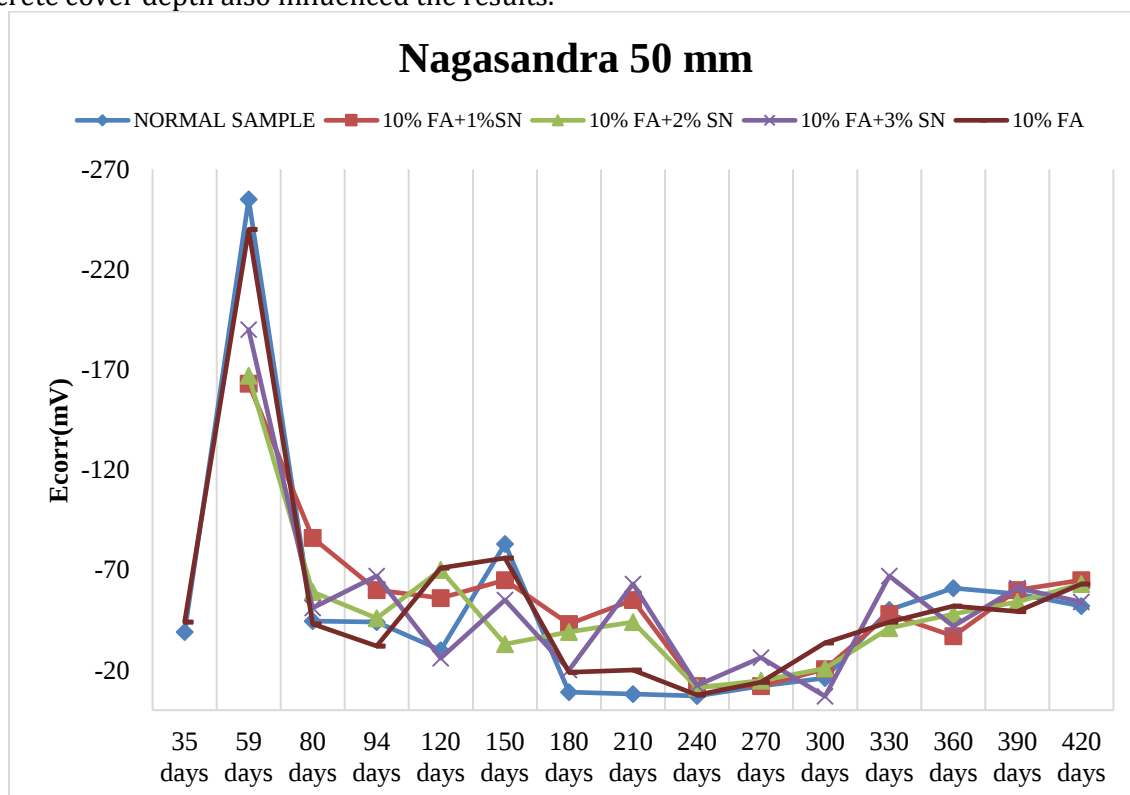


Figure 2. Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth.

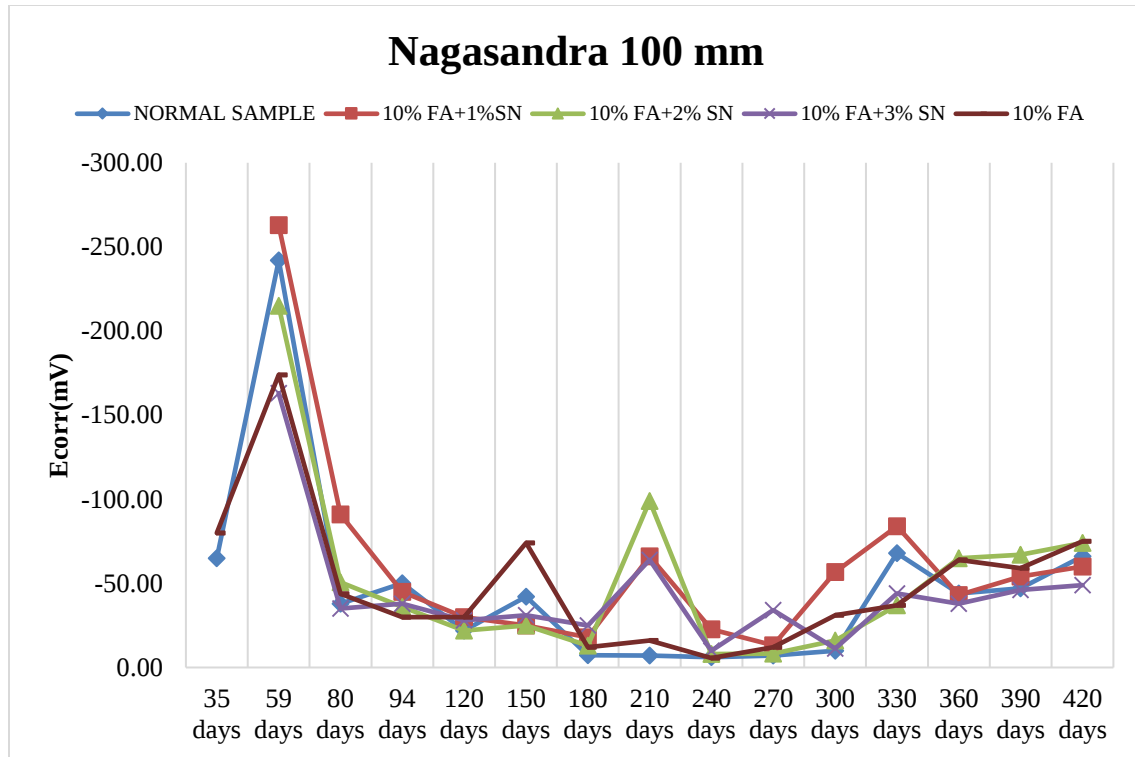


Figure 3. Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth.

4.2 Bellandur STP:

Figures 4 and 5 quantitatively present half-cell potential (E_{corr}) trends for reinforced concrete made with secondary treated wastewater, incorporating 10% fly ash and sodium nitrite at 1%, 2%, and 3% by cement weight. E_{corr} measurements were tracked over a 14-month period for concrete cover depths of 50 mm and 100 mm. At 50 mm cover, the control sample initially showed higher corrosion activity, with E_{corr} values near -270 mV at 30–60 days, well within the uncertain corrosion range (-200 to -350 mV per ASTM C876-15). In contrast, the 1% and 2% sodium nitrite samples maintained E_{corr} values between -180 mV and -200 mV during the same period, indicating a less than 10% probability of corrosion. The 3% sample exhibited a dip below -200 mV around 240 days, reaching approximately -220 mV, suggesting moderate corrosion

risk during that interval. However, by 420 days, all sodium nitrite-treated samples stabilized within -100 mV to -150 mV, clearly indicating passive corrosion conditions. For 100 mm cover, the trends were similar but improved. The control's E_{corr} initially reached -250 mV, but gradually stabilized to around -180 mV. Sodium nitrite-treated samples showed better consistency: the 2% mix maintained values between -90 mV and -130 mV throughout, while the 3% mix fluctuated slightly (reaching -170 mV at 180 days) before aligning with the 2% performance by the end of the study. Overall, the 2% sodium nitrite dosage provided the most stable and consistently high E_{corr} values, especially at 100 mm cover, confirming its effectiveness in reducing corrosion probability in STW-based concrete.

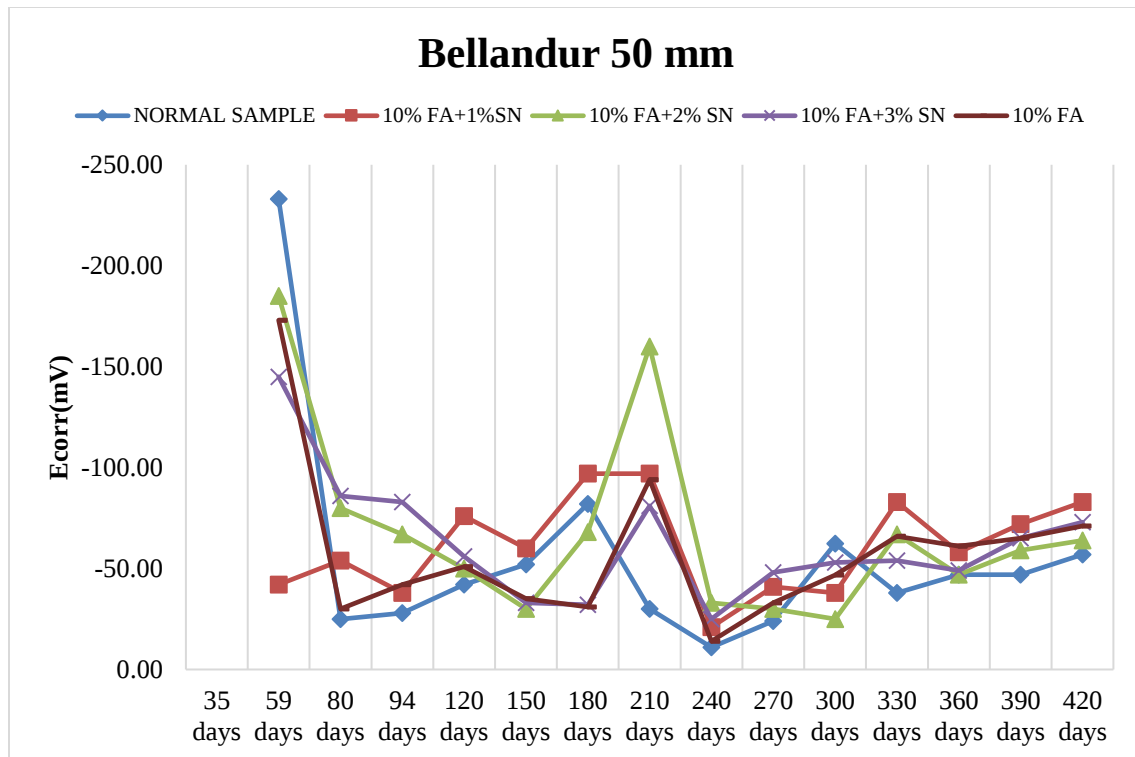


Figure 4. Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth

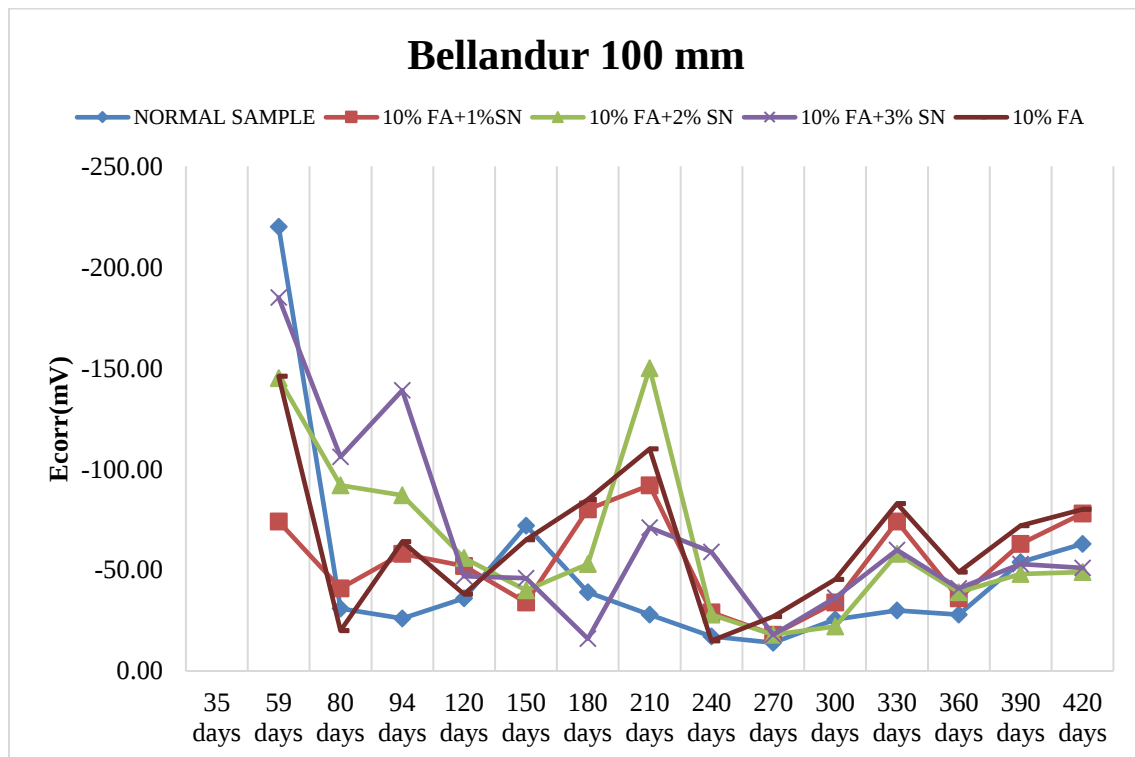


Figure 5. Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth.

4.3 Jakkur STP:

Figures 6 and 7 quantitatively illustrate the half-cell potential (E_{corr}) results for concrete made with secondary treated wastewater (STW) from the Jakkur region, incorporating 10% fly ash and varying sodium nitrite dosages (1%, 2%, and 3% by cement weight), compared to a potable water control. At a 50 mm cover depth (Figure 6), the potable water sample consistently exhibited superior corrosion resistance, maintaining E_{corr} values between -30 mV and -80 mV over the 420-day period—indicating less than a 10% probability of corrosion. The STW control sample initially recorded more negative values, dropping to approximately -230 mV at 60 days, but improved to around -180 mV by the end of the study. Sodium nitrite-modified mixes showed improved performance, with 1% and 2% dosages maintaining E_{corr} values between -70 mV and -150 mV, firmly within the low-risk corrosion zone. The 3% dosage showed slight fluctuations, with values occasionally approaching -190 mV around 240 days, but overall remained above -200 mV. At 100 mm cover depth, all samples showed enhanced corrosion

resistance due to the increased concrete cover. The potable water sample again performed best, with values consistently between -20 mV and -60 mV. The STW control stabilized around -130 mV to -150 mV, while the sodium nitrite-treated samples (particularly 1% and 2%) maintained more stable and positive potentials between -60 mV and -120 mV. Although the 3% dosage showed some variation, it eventually stabilized near -130 mV. These results confirm that the use of sodium nitrite, especially at 1% and 2%, significantly enhances the corrosion resistance of STW-based concrete. Combined with 10% fly ash and a 100 mm cover depth, the modified mixes maintained E_{corr} values above -200 mV, indicating a less than 10% probability of corrosion and validating the durability of sustainable concrete using treated wastewater. Overall, the 2% sodium nitrite dosage provided the most stable and consistently high E_{corr} values, especially at 100 mm cover, confirming its effectiveness in reducing corrosion probability in STW-based concrete.

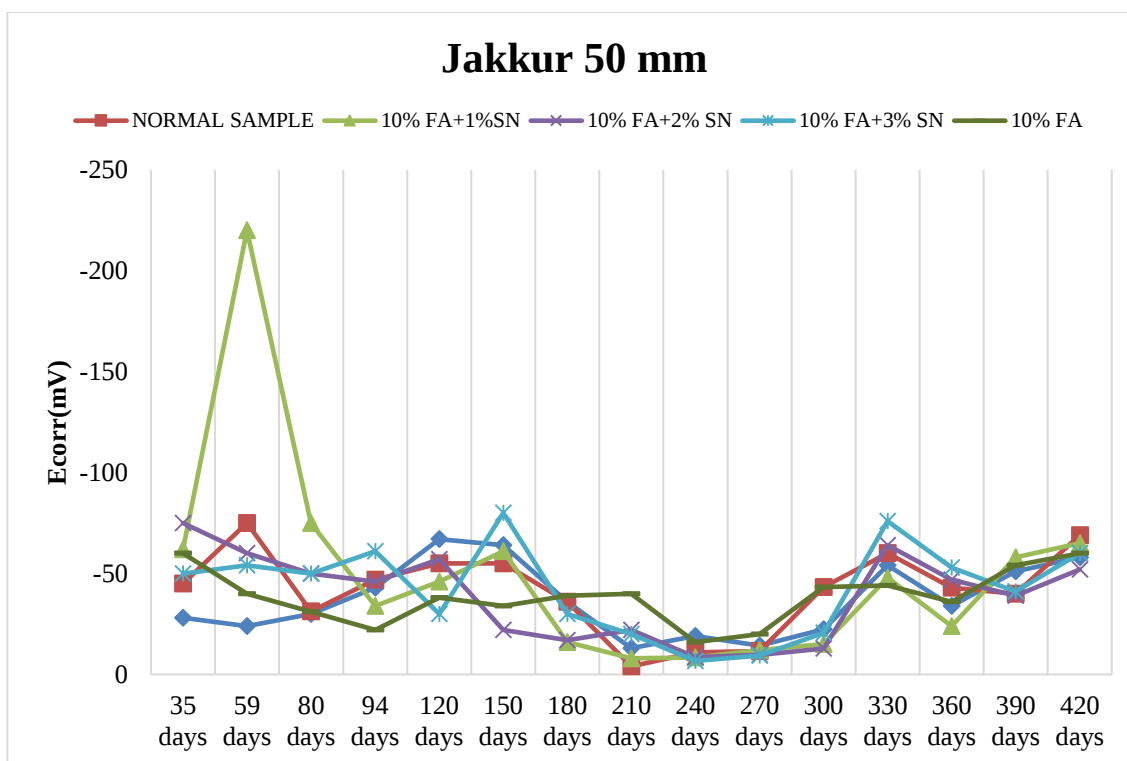


Figure 6. Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth

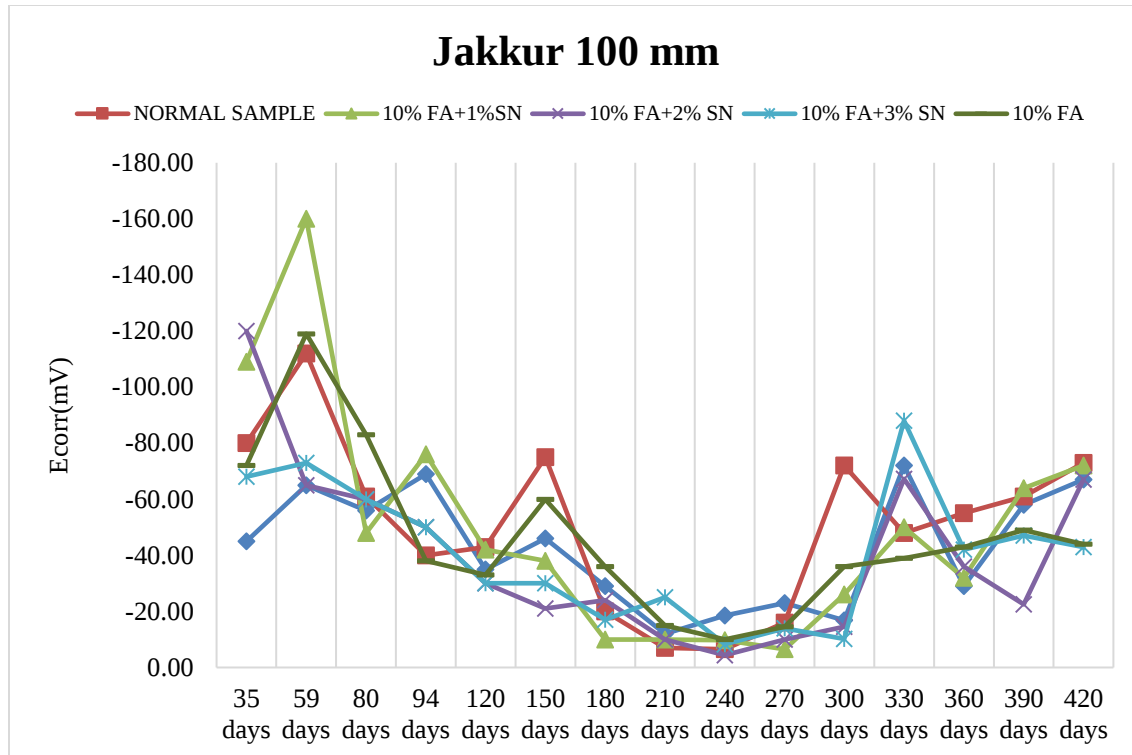


Figure 6. Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth

5. Conclusion

- **Effectiveness of the Half-Cell Potentiometer Test:** The half-cell potentiometer test serves as a crucial non-destructive method for evaluating the corrosion risk in reinforced concrete structures, allowing engineers to assess the condition of embedded steel without compromising the integrity of the structure.
- **Impact of Material Modifications:** Incorporating 10% fly ash as a partial cement replacement, along with 1-3% sodium nitrite, significantly enhances the corrosion resistance of concrete. Fly ash increases the density of the concrete matrix, reducing chloride ingress, while sodium nitrite functions as an effective corrosion inhibitor.
- **Performance Based on Cover Depth:** Increasing the cover depth from 50 mm to 100 mm substantially lowers the corrosion risk, as indicated by more positive (less negative) half-cell potential values. This highlights the importance of adequate concrete cover in extending the lifespan of reinforcement.
- **Effectiveness of Sodium nitrite:** Sodium nitrite concentrations of 1% and 2% by weight of cement were the most effective in maintaining

corrosion potential values above -200 mV, indicating a low likelihood of corrosion. At a 3% concentration, the performance was inconsistent, suggesting that higher sodium nitrite levels may not yield proportional benefits.

- **Influence of Water Source:** The use of secondary treated wastewater in concrete was evaluated and compared to potable water. The results show that with the appropriate material modifications (fly ash and sodium nitrite), secondary treated wastewater can be used effectively without significantly increasing the risk of corrosion.

Practical Advantages: The half-cell potentiometer test provides a fast, accurate, and economical solution for assessing the condition of concrete structures. It allows for early detection of potential corrosion issues, enabling proactive maintenance and reducing long-term repair costs.

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