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Corrosion Studies on Reinforced Concrete Produced With Secondary Treated Wastewater and Fly Ash with Sodium Nitrite as Corrosion Inhibitor

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Abstract - This study investigates the feasibility of utilizing secondary treated wastewater (STW) as a sustainable alternative to potable water for concrete production, focusing on its impact on steel reinforcement corrosion. Concrete samples of M30 grade were prepared with 10% fly ash as a partial cement replacement and varying sodium nitrite concentrations (1%, 2%, and 3% by weight of cement) as corrosion inhibitors. The corrosion activity was assessed over a 420-day period using the half-cell potentiometer test, a standardized non-destructive method (ASTM C876-15). The study analyzed corrosion potentials at two concrete cover depths (50 mm and 100 mm) across samples prepared with STW from three treatment plants in Bangalore: Bellandur, Jakkur, and Nagasandra. Results showed that sodium nitrite effectively reduced corrosion risk, particularly at 1% and 2%, where corrosion potentials remained above -200 mV after 420 days, indicating less than a 10% probability of corrosion. A 100 mm cover depth provided better corrosion protection compared to 50 mm, emphasizing the importance of sufficient cover. STW samples with higher residual chlorides and dissolved solids showed initial susceptibility, but the combination of fly ash and sodium nitrite mitigated corrosion effectively. By the end of 420 days, the treated samples demonstrated corrosion performance comparable to potable water. This study confirms that with proper modifications, STW can be a viable alternative in concrete mixing, contributing to sustainable construction practices while maintaining structural integrity and durability over extended periods.

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

1. Introduction

Concrete production is heavily dependent on water and cement, which has a significant impact on the environment. To produce concrete each year, approximately 2.5 tons (over one cubic meter) of cement and 1 billion tons of water are used[1]. Preparing concrete typically requires 150 to 210 liters of water per cubic meter. In 1997, the concrete industry consumed over 800 billion liters of water, with projections suggesting this Fig could rise to 900 billion liters by 2030[2,3]. This immense water demand places considerable pressure on already scarce freshwater resources, particularly in the face of growing urbanization. The quality of water used during mixing is critical to concrete performance. While alternative water sources, such as treated wastewater, can help reduce reliance on freshwater, they often contain organic and inorganic compounds that can impede cement hydration[4,5,6]. These substances can extend the setting time of cement, negatively affecting both the fresh and hardened properties of concrete. Water purity is therefore a crucial factor in ensuring optimal concrete production. A practical solution to address water scarcity is the use of secondary treated wastewater (effluent) from wastewater treatment plants. Domestic wastewater originates from various sources, such as residential complexes, commercial establishments, and other facilities, which is transported via sewers[7,8]. Treated effluent can be repurposed for applications like irrigation, industrial processes, and horticulture. In India, the use of effluents in construction and concrete activities is regulated by several government bodies and agencies, including the Central Pollution Control Board (CPCB), Bureau of Indian Standards (BIS), State Pollution Control Boards (SPCBs), and local municipal authorities. International guidelines from organizations like the Occupational Safety and Health Administration (OSHA) in the United States, the Health and Safety Executive (HSE) in the United Kingdom, and the International Labour Organization (ILO) also offer relevant insights[9,10]. Additionally, industry-specific standards from entities like the American Concrete Institute (ACI) provide guidance on incorporating effluent in concrete production[11]. To ensure sustainable practices, government agencies such as the Bangalore Water Supply and Sewerage Board (BWSSB), responsible for water supply and wastewater management in Bengaluru, should oversee and regulate concrete manufacturing, particularly in ready-mix concrete (RMC) plants.

Corrosion of reinforcement in concrete is a critical issue that significantly impacts the durability, safety, and longevity of reinforced concrete structures. Reinforced concrete combines the compressive strength of concrete with the tensile strength of steel reinforcement, making it a widely used construction material. However, when the steel reinforcement within the concrete begins to corrode, it compromises the structural integrity and can lead to premature deterioration. Corrosion typically occurs when the protective alkaline environment of the concrete is disrupted, exposing the embedded steel to aggressive environmental elements like moisture, oxygen, and chloride ions[12,13]. Factors such as carbonation (the reaction of carbon dioxide with the concrete surface) and chloride ingress from de-icing salts or marine environments are common triggers. The formation of rust, which has a greater volume than the original steel, is a result of the corrosion process and can lead to internal pressure and cracking within the concrete. The quality of materials used in their production, including water, has a significant impact on the durability and longevity of reinforced concrete structures[14]. With growing environmental concerns and water scarcity, the use of secondary treated wastewater as a substitute for freshwater in concrete mixing has gained attention. While this practice offers sustainable benefits, it also introduces potential challenges, particularly regarding the corrosion of reinforcement embedded within the concrete. Secondary treated wastewater may contain residual inorganic salts, chlorides, sulfates, and organic compounds that can alter the electrochemical environment surrounding the reinforcing steel. These substances may increase the risk of corrosion, compromising the structural integrity and service life of the concrete[15]. The corrosion process starts when aggressive agents penetrate the concrete matrix, causing the protective passive layer on the steel surface to break down and accelerate the degradation process. Understanding the impact of treated wastewater on concrete properties and reinforcement corrosion is critical for ensuring structural performance and durability. This introduction sets the stage for evaluating the feasibility and challenges associated with incorporating secondary treated wastewater in concrete production while addressing potential mitigation measures to enhance its long-term sustainability[16,17,18].

The half-cell potentiometer is a widely used non-destructive testing device for assessing the corrosion activity of reinforcement in concrete structures. It measures the electrical potential difference between a reference electrode and the reinforcing steel embedded in concrete, providing insight into the likelihood of corrosion[19,20]. This method is based on electrochemical principles, where variations in potential indicate the presence and extent of corrosive activity. A standard setup typically includes a reference electrode, such as a copper-copper sulfate or silver-silver chloride electrode, placed on the concrete surface, and a connection to the reinforcing steel. The readings obtained are compared to established potential ranges, which help determine the corrosion probability. For example, higher negative potentials usually indicate active corrosion, while lower potentials suggest passive or stable steel conditions[21,22]. The half-cell potentiometer is particularly valuable for monitoring structures exposed to aggressive environments or made with alternative materials, such as secondary treated wastewater. It enables engineers to identify areas of concern, prioritize repairs, and evaluate the effectiveness of corrosion mitigation strategies, ensuring the durability and safety of concrete structures. To assess the likelihood and extent of reinforcement corrosion, the study employed the half-cell potentiometer method, a widely recognized non-destructive technique[23,24]. This method provides electrochemical potential measurements that indicate the probability of corrosion activity within the concrete. By correlating these measurements with the water quality, admixture content, and fly ash replacement levels, the study aimed to provide comprehensive insights into the feasibility of using treated wastewater in reinforced concrete applications[25].

Concrete was produced using a mix that incorporated 10% fly ash as a partial replacement for cement and sodium nitrite, an accelerating admixture, in varying proportions of 1%, 2%, and 3% by weight of cement. Additionally, secondary treated wastewater sourced from three different secondary-level wastewater treatment plants was used as the mixing water. This sustainable approach aimed to evaluate the potential of treated wastewater in concrete production while enhancing the material’s performance through the use of fly ash and admixtures. The primary objective of this study was to examine the corrosion behavior of steel reinforcement in concrete made with secondary treated wastewater. Corrosion of reinforcement poses significant durability concerns, particularly when alternative water sources are used in concrete manufacturing, as they may contain residual salts or compounds that can influence the electrochemical stability of the steel.

2.0 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 of a Half-Cell Potentiometer employed for this assessment.

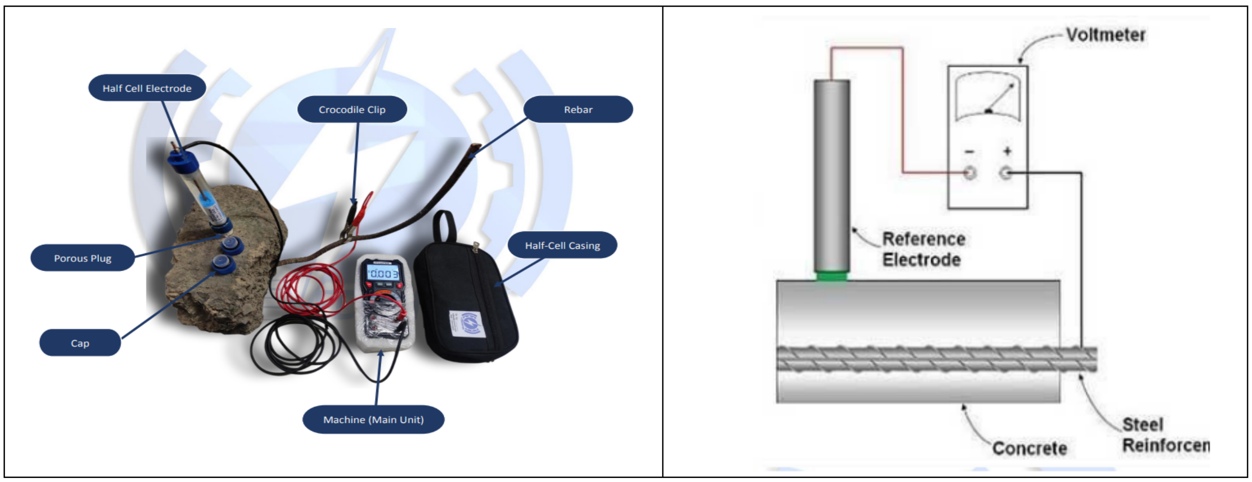

Fig 1: Assembly and Working of Half-cell potentiometer

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 +999mV, 2. Accuracy: +-5mV, 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

3.0 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 C 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.

3.2 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 ± 2°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/m3)	Fly ash (kg/m3)	Coarse aggregate (kg/m3)	Fine aggregate (kg/m3)	Sodium Nitrite (kg/m3)	Water (kg/m3)	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	STW from Nagasandra treatment plant
N-FA-10	369.0	41.0	1069.3	650.0	0.0	216.5	
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	

3.3.2 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 pours 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/CuSO4	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:

The provided graphs Fig 2 and 3 represent the half-cell potential (E_corr) measurements for steel reinforcement in concrete made using secondary treated wastewater, with 10% fly ash as a cement replacement and sodium nitrite (1%, 2%, and 3% by weight of cement) as an accelerating admixture. The results are presented for two concrete cover depths 50 mm and 100 mm over a testing period of 35 to 420 days. The graphs compare these samples with a normal sample (control). At 59 days, the normal sample shows potentials around -270 mV, which falls in the uncertain probability range (-200 to -350 mV). This suggests a moderate likelihood of corrosion activity. In contrast, the samples with 1%, 2%, and 3% sodium nitrite show less negative potentials (closer to -150 mV), indicating a less than 10% probability of corrosion activity. Over time, by 180 days and beyond, all treated samples stabilize with potentials closer to -50 mV, falling well into the range indicating less than 10% probability of corrosion activity. This suggests that sodium nitrite, particularly at 3%, is effective in reducing the corrosion likelihood. The normal sample remains closer to -200 mV, hovering near the threshold of uncertain activity, showing comparatively higher corrosion susceptibility. At 59 days, the normal sample records a potential of around -300 mV, which lies in the uncertain probability range (-200 to -350 mV). This indicates possible corrosion activity but not with high certainty. The sodium nitrite-treated samples show potentials between -100 mV and -200 mV, corresponding to a less than 10% probability of corrosion activity. By 420 days, the treated samples consistently show potentials close to -50 mV, well within the safe range indicating no significant corrosion activity. The normal sample stabilizes around -200 mV, which still borders on the uncertain zone but shows no significant corrosion compared to earlier stages.

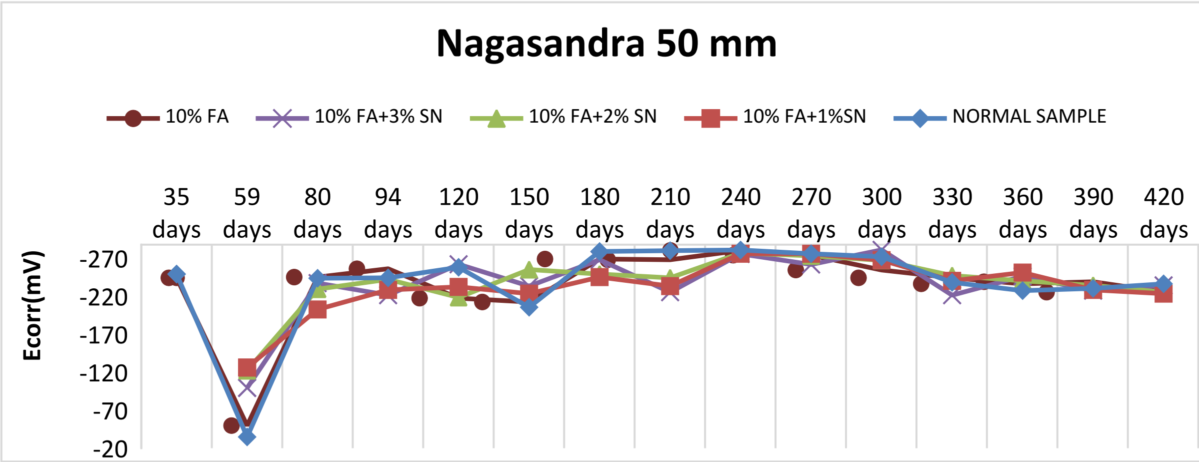

Fig 2: Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth.

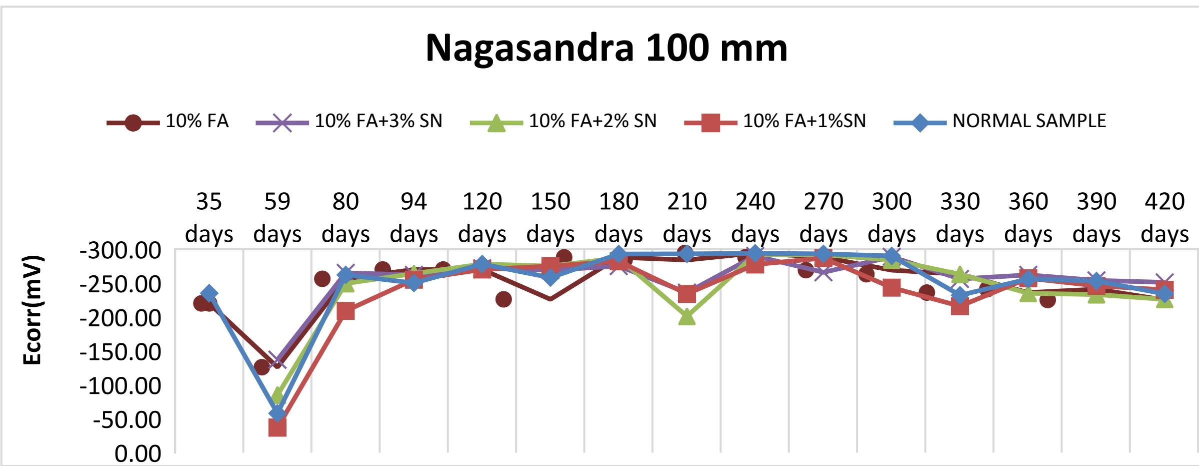

Fig 3: Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth.

4.2 Bellandur STP:

Fig 4 and 5 shows The results of the half-cell potentiometer test for concrete made with secondary treated wastewater, incorporating 10% fly ash as a cement replacement along with 1%, 2%, and 3% sodium nitrate ($NaNO_2$) by weight of cement, are presented in the graphs. The data show variations in the corrosion potential (Ecorr) over a 420-day period for two cover depths: 50 mm and 100 mm. At a cover depth of 50 mm, the normal sample shows higher corrosion activity initially, with Ecorr values exceeding -200 mV during the early days, indicating less than 10% probability of steel corrosion activity. However, samples with $NaNO_2$ exhibit improved performance, especially at 1% and 2%, where the corrosion potential remains closer to or above -200 mV, reflecting minimal corrosion risk. The 3% $NaNO_2$ sample occasionally dips below -200 mV, particularly around 240 days, suggesting fluctuating corrosion probabilities. By the end of the monitoring period, all modified samples show stabilization around -100 mV to -150 mV, indicating low corrosion risk.

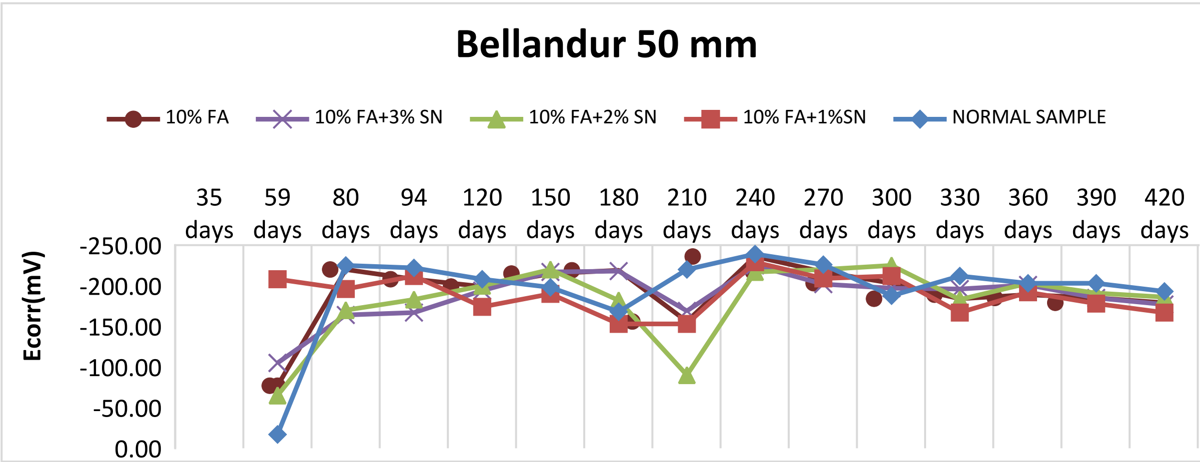

Fig 4: Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth.

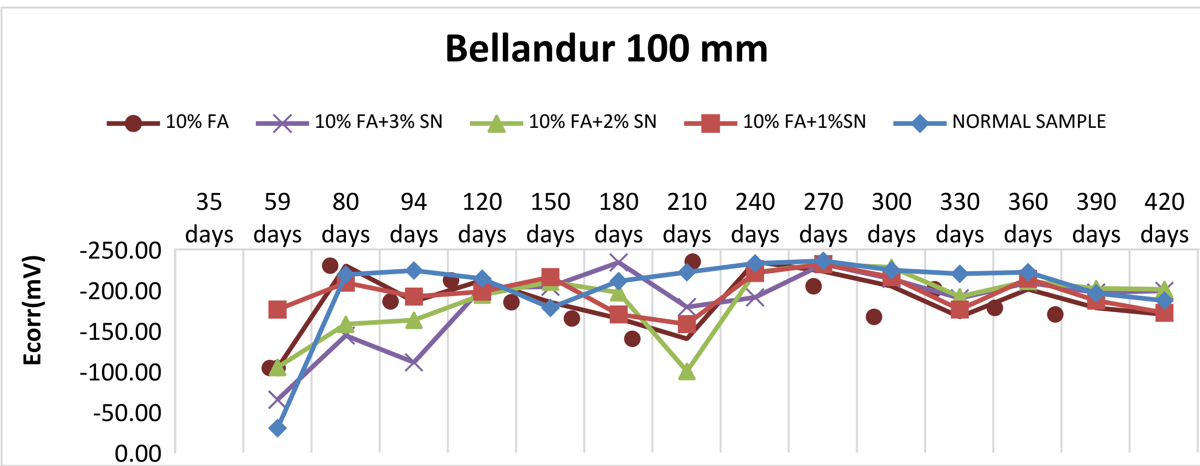

Fig 5: Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth.

For the 100 mm cover depth, as shown in Fig 6 a similar trend is observed, but with generally more stable and less negative Ecorr values throughout the testing period, which aligns with the enhanced protection offered by increased cover thickness. The normal sample shows a higher tendency for corrosion initially but stabilizes to lower-risk values over time. The addition of $NaNO_2$, particularly at 2%, demonstrates a noticeable reduction in the corrosion probability, with the Ecorr values mostly staying above -200 mV. The 3% $NaNO_2$ sample shows a slight inconsistency at intermediate periods but achieves similar stability toward the later stages.

4.3 Jakkur STP:

Fig 6 and 7 shows the half-cell potentiometer results for concrete samples made with secondary treated wastewater, incorporating 10% fly ash as a cement replacement and varying concentrations of sodium nitrate ($NaNO_2$) at 1%, 2%, and 3%, are depicted in the graphs for the Jakkur region at cover depths of 50 mm and 100 mm. The study also includes a portable water sample for comparison. At 50 mm cover depth, the portable water sample consistently exhibits higher corrosion potential (Ecorr), remaining above -200 mV throughout the monitoring period, indicating less than a 10% probability of steel corrosion. The normal sample shows slightly more negative values initially, dipping to -200 to -250 mV during the early days but stabilizing above -200 mV by the end of the period. Samples with $NaNO_2$ show improved corrosion resistance, with

1% and 2% concentrations exhibiting Ecorr values mostly between -50 mV and -150 mV. The 3% $NaNO_2$ sample shows occasional fluctuations but remains in the low-risk zone (>-200 mV) overall.

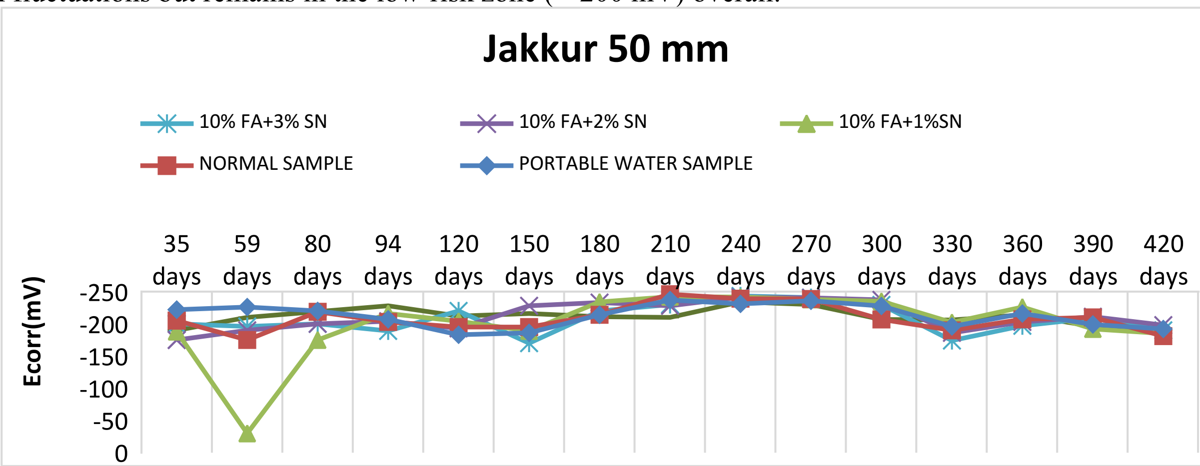

Fig 6: Graphical representation of Corrosion Resistance of concrete of 50 mm cover depth.

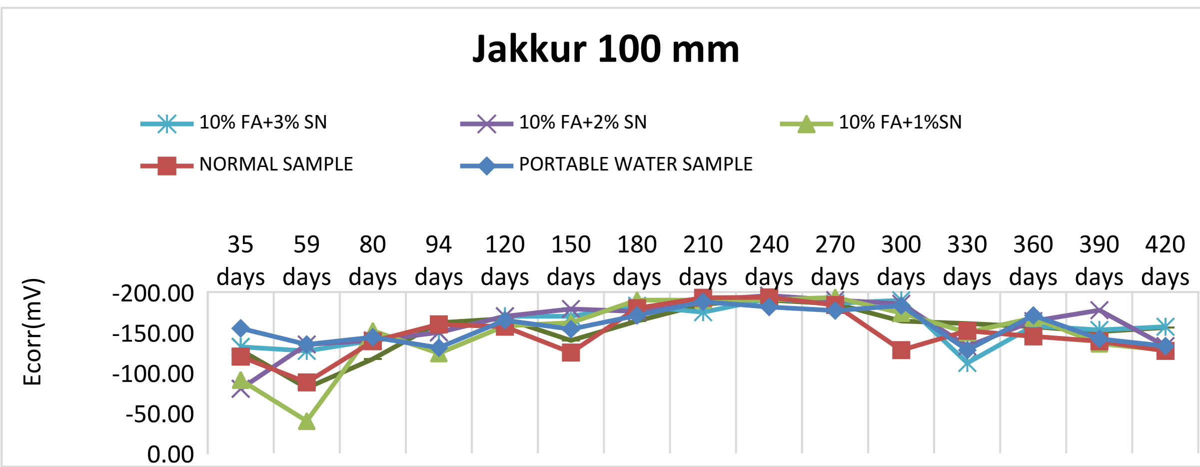

Fig 7: Graphical representation of Corrosion Resistance of concrete of 100 mm cover depth.

Fig 7 shows the 100 mm cover depth, all samples demonstrate reduced corrosion potential compared to the 50 mm cover depth, owing to the increased protective layer against chloride ingress. The normal sample and $NaNO_2$-modified samples show similar trends, with Ecorr values stabilizing around -100 mV to -150 mV, indicating a low probability of steel corrosion. The portable water sample retains the highest performance, consistently exhibiting Ecorr values above -50 mV throughout the 420-day duration. The results validate the effectiveness of sodium nitrate, particularly at 1% and 2%, in enhancing the corrosion resistance of concrete made with secondary treated wastewater. The combination of fly ash and sodium nitrate provides synergistic benefits in reducing corrosion probability, with the 100 mm cover depth further enhancing the durability of the concrete. These findings align with the classification, confirming that Ecorr values above -200 mV correspond to less than a 10% probability of steel corrosion.

5.0 Conclusion

- Effectiveness of Half-Cell Potentiometer Test: The half-cell potentiometer test proves to be an essential non-destructive tool for assessing the likelihood of corrosion in reinforced concrete structures. It enables engineers to predict the state of embedded steel without damaging the structural integrity.
- Influence of Material Modifications: Incorporating 10% fly ash as a partial cement replacement, along with 1–3% sodium nitrate, improves the corrosion resistance of concrete. Fly ash enhances the concrete matrix's density, reducing chloride ingress, while sodium nitrate acts as a corrosion inhibitor.
- Performance with Cover Depth: Increased cover depth (from 50 mm to 100 mm) significantly reduces corrosion risk, as evidenced by more positive (less negative) half-cell potential values. This demonstrates the importance of adequate concrete cover in prolonging reinforcement durability.
- Validation of Sodium Nitrate Effectiveness: Sodium nitrate concentrations of 1% and 2% by weight of cement were most effective in maintaining corrosion potential values above -200 mV, indicating a low probability of corrosion. At 3% concentration, performance was inconsistent, suggesting that excessive sodium nitrate may not provide proportional benefits.
- Impact of Water Source: The use of secondary treated wastewater in concrete was assessed and compared against portable water. The results demonstrate that with proper material modifications (fly ash and sodium nitrate), secondary treated wastewater can be effectively utilized without significantly increasing corrosion risks.

Practical Advantages: The half-cell potentiometer test offers a quick, reliable, and cost-effective method for monitoring the health of concrete structures, enabling timely intervention and reducing maintenance costs.

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