

PROTECTIVE PERFORMANCE OF THE MIGRATING CORROSION INHIBITOR MCI-VN FOR STEEL REINFORCEMENT IN CONCRETE PORE SOLUTION

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- Highlights:

- ✓ A blended corrosion inhibitor (MCI-VN) based on inorganic and organic salts with a nonionic surfactant was developed for reinforcing steel in chloride-containing concrete environments.
- ✓ Electrochemical tests (potentiodynamic polarization and impedance spectroscopy) in concrete pore solution with 3% NaCl showed 92–97% inhibition efficiencies at concentrations of 2.0–5.0 wt.%.
- ✓ Gravimetric experiments over 30 days demonstrated complete corrosion suppression at $C_{inh} \geq 2.0$ wt.% for MCI-VN, while IFKhAN-80 required $C_{inh} \geq 3.0$ wt.% to achieve the same effect.
- ✓ Comparative evaluation confirmed that MCI-VN exhibited slightly higher protective performance than the commercial inhibitor IFKhAN-80 under equivalent conditions.

- **Abstract:** A blended corrosion inhibitor (MCI-VN) based on a synergistic combination of inorganic and organic salts with a nonionic surfactant is proposed to protect steel reinforcement in concrete under chloride exposure. The composition is suitable for use as an admixture in the production of new reinforced concrete structures or repair mortars, as well as for surface application to existing structures (migrating corrosion inhibitor). This study evaluates the anti-corrosion properties of the inhibitor in the concrete pore solution. The assessment was performed using electrochemical methods (potentiodynamic polarization and impedance spectroscopy) and gravimetric analysis. As the inhibitor concentration (C_{inh}) increased in the 0.25–5.0 wt.% range, the inhibition efficiency rose to 92–97%, depending on the evaluation method. During 30-day gravimetric experiments, complete suppression of corrosion was observed at $C_{inh} \geq 2.0$ wt.%. Comparison with the commercial inhibitor IFKhAN-80 showed comparable or superior protective performance under equivalent conditions. Therefore, MCI-VN can be considered an effective solution for improving

the corrosion resistance of reinforced concrete structures in chloride-containing environments.

- **Keywords:** *Reinforcing steel, corrosion inhibitors, chlorides, reinforced concrete, concrete pore solution.*

1. INTRODUCTION

Reinforced concrete is one of the most widely used materials in civil and industrial infrastructure construction. Reinforced concrete structures are degraded when exposed to environmental factors containing aggressive agents (such as chlorides, carbon dioxide, sulfates, acids, etc.) [1]. The financial costs associated with maintaining the integrity and safety of reinforced concrete (RC) structures were estimated at 18–21 billion USD annually in the United States as of 2014 [2]. Indirect costs, including traffic disruptions and reduced operational efficiency, can exceed direct expenses by up to tenfold [3].

Chloride-induced corrosion of steel reinforcement is the primary cause of reinforced concrete deterioration [4, 5]. This issue is particularly relevant for marine infrastructure (e.g., ports, hydraulic structures), facilities in the chemical industry (e.g., salt extraction, fertilizer production), and transportation structures located near coastlines or in regions where deicing treatments are applied during winter. A distinguishing feature of chloride-induced corrosion in concrete is its localized nature [6]. Pitting and crevice corrosion can develop rapidly, leading to partial or complete structural failure. This form of corrosion is more difficult to detect than uniform corrosion, such as that caused by concrete carbonation [7].

Various methods have been developed to enhance the durability of concrete structures. One practical approach for protecting steel reinforcement from corrosion is using inhibitors [8–10]. These compounds can be introduced into the concrete mix during construction or into repair mortars (so-called admixture inhibitors) or applied to the surface of existing structures in the form of migrating corrosion inhibitors (MCIs) [11]. A literature review indicates that one of the most effective classes of corrosion inhibitors comprises blended formulations [12]. These typically contain organic and inorganic components and additional substances designed for application as MCIs. One such commercially available inhibitor is IFKhAN-80 (TU 2458-005-66126292-11, IPCE RAS, Russia) [13].

In Vietnam, chloride-induced corrosion has emerged as a critical durability issue for reinforced concrete infrastructure. Field investigations of coastal piled-pier port structures have revealed significant rebar corrosion and structural damage occurring as early as 10–15 years into service, with widespread deterioration commonly observed within 20–25 years [14]. In light of the absence of domestically produced migrating corrosion inhibitors, developing a locally manufactured solution is essential to ensure cost-effective and accessible corrosion protection for national infrastructure.

Accordingly, a novel corrosion inhibitor composition (MCI-VN) has been

developed as either an admixture in fresh concrete or repair formulations or a migrating corrosion inhibitor. The MCI-VN formulation is based on a synergistic combination of inorganic and organic salts with a nonionic surfactant. This study aims to evaluate the efficacy of the migrating corrosion inhibitor MCI-VN in model aqueous solutions to protect reinforcing steel in the presence of chlorides and to compare its anti-corrosion performance with that of the commercial product IFKhan-80.

2. MATERIALS AND METHODS

2.1. Materials

The MCI-VN formulation was prepared by blending the following components (by weight): sodium hydroxide (NaOH) - 1.73 g, benzoic acid (C_6H_5COOH) - 5.31 g, sodium nitrite ($NaNO_2$) - 20.97 g, glycerol - 1.00 g, nonionic surfactant (cocamide diethanolamine) - 0.50 g, diethanolamine (DEA) - 0.50 g. The remaining portion of the 100 g formulation consisted of deionized water. This mixture was homogenized until the complete dissolution of all components was achieved, and it was used directly in corrosion testing.

Smooth-surfaced reinforcing steel of grade CB300-T, conforming to TCVN 1651-1:2018, with a diameter of 10 mm, was used as the test material. The elemental composition of the steel, determined according to ASTM E415:2021, was (wt.%): Fe 98.518, C 0.236, Mn 0.413, Si 0.155, P 0.012, S 0.044, Ni 0.131, Cr 0.035, Cu 0.334, Mo 0.010, V 0.002, Ti 0.001, Al 0.016, Nb 0.001, W 0.005, Sn 0.037, Co 0.009, Pb 0.019, and Zn 0.023. For the potentiodynamic and impedance spectroscopy measurements, one end of each steel rod was soldered to an insulated copper wire, and the soldered area was coated with epoxy resin.

The concrete pore solution was prepared by extracting crushed mortar with single-distilled water for 24 hours. The mass ratio of water to solid material was maintained at 1:10. The resulting solution was filtered through folded paper filters. The mortar was prepared from a cement-sand mixture consisting of PCB40 Portland cement (Nghi Son), whose composition (wt.%) was SiO_2 22.0, Al_2O_3 8.0, CaO 62.0, Fe_2O_3 3.0, MgO 2.1, SO_3 2.1, K_2O 0.6, and Na_2O 0.2, and dry, washed quartz sand with a particle size range of 0.20-0.63 mm. The cement-to-sand mass ratio was 1:2, and the water-to-cement ratio was set at $w/c = 0.4$.

2.2. Methods

A combination of electrochemical and gravimetric measurements was employed to evaluate the protective performance of the proposed formulation and the commercial inhibitor IFKhan-80.

The surface of the steel electrodes was polished using P1000 sandpaper (Al_2O_3 abrasive with a particle size of 14-20 μm) to a cleanliness grade of St3 following ISO 8501-1:2014 [15] and then degreased with 96% ethanol.

Potentiodynamic polarization curves were recorded in a concrete pore solution with the addition of 3% NaCl. The corrosion current density (i_{cor}) was calculated using

the linear polarization resistance method proposed by F. Mansfeld [16]. A three-electrode glass cell was used, with the working, counter, and reference electrodes in a single compartment under natural aeration. The working electrode was positioned such that the thickness of the solution above its surface was maintained at 20 ± 2 mm. A platinum mesh served as the counter electrode. The silver/silver chloride (Ag/AgCl) reference electrode was placed in a separate vessel connected to the cell via a salt bridge made of agar-agar gel containing KNO_3 to prevent chloride contamination of the test solution. The reference electrode potential was +201 mV versus the standard hydrogen electrode (SHE). Polarization curves were recorded using a potentiostat/galvanostat (Autolab PGSTAT, Netherlands) after stabilizing the open circuit potential (E_{cor}) for 60 minutes. The scan rate was 0.2 mV/s. The working electrode potential (E) is reported versus the Ag/AgCl scale, and the current density (i) was calculated for the geometric surface area of the working electrode, which ranged from 7.0 to 8.5 cm^2 , depending on the experiment.

The ability of the investigated formulations to reduce the corrosion rate was evaluated based on the inhibition efficiency, which was calculated using the following equation:

$$Z_{\text{inh}} = \frac{i_{\text{cor},0} - i_{\text{cor,inh}}}{i_{\text{cor},0}} \cdot 100\% \quad (1)$$

where $i_{\text{cor},0}$ and $i_{\text{cor,inh}}$ are the corrosion current densities in the blank (control) experiment and the presence of the inhibitor, respectively.

Electrochemical impedance spectra were recorded using a potentiostat/galvanostat (Autolab PGSTAT, Netherlands). After stabilizing the open circuit potential (E_{cor}) for 60 minutes, the frequency response was measured from 0.01 Hz to 50 kHz under open-circuit (zero-current) conditions.

The analysis of the frequency dependence, selection of the equivalent electrical circuit, and determination of the nominal values of its elements were performed using the DCS software package. The results were presented in the form of Nyquist plots. The inhibition efficiency (η_{inh}) was calculated using the following equation:

$$\eta_{\text{inh}} = \left(1 - \frac{R_{\text{p},0}}{R_{\text{p,inh}}}\right) \cdot 100\% \quad (2)$$

where $R_{\text{p},0}$ and $R_{\text{p,inh}}$ are the polarization resistances in the control experiment and the presence of the inhibitor, respectively.

Corrosion-induced mass loss was monitored over 30 days using unstressed (non-polarized) steel specimens. Corrosion products were removed following ISO 8407:2021 [17]. The corrosion inhibition efficiency of the tested formulations was also evaluated based on mass loss data using the following equation:

$$Z_{\text{weigh}} = \frac{m_{\text{weigh},0} - m_{\text{weigh,inh}}}{m_{\text{weigh},0}} \cdot 100\% \quad (3)$$

where $m_{\text{weigh},0}$ and $m_{\text{weigh},\text{inh}}$ are the corrosion rates determined from mass loss measurements in the control experiment and the presence of the inhibitor, respectively. Visual inspection of the surface of the reinforcing steel specimens was also carried out.

3. RESULTS

Introducing MCI-VN into the concrete pore solution containing 3% NaCl resulted in a shift of the corrosion potential (E_{cor}) in the anodic direction. As the inhibitor concentration (C_{inh}) increased from 0.25 wt.% to 5.0 wt.%, the magnitude of this shift increased from 50 to 180 mV (Table 3). Increasing the concentration of MCI-VN also reduced current densities in both the anodic and cathodic branches of the polarization curves (Figure 1b).

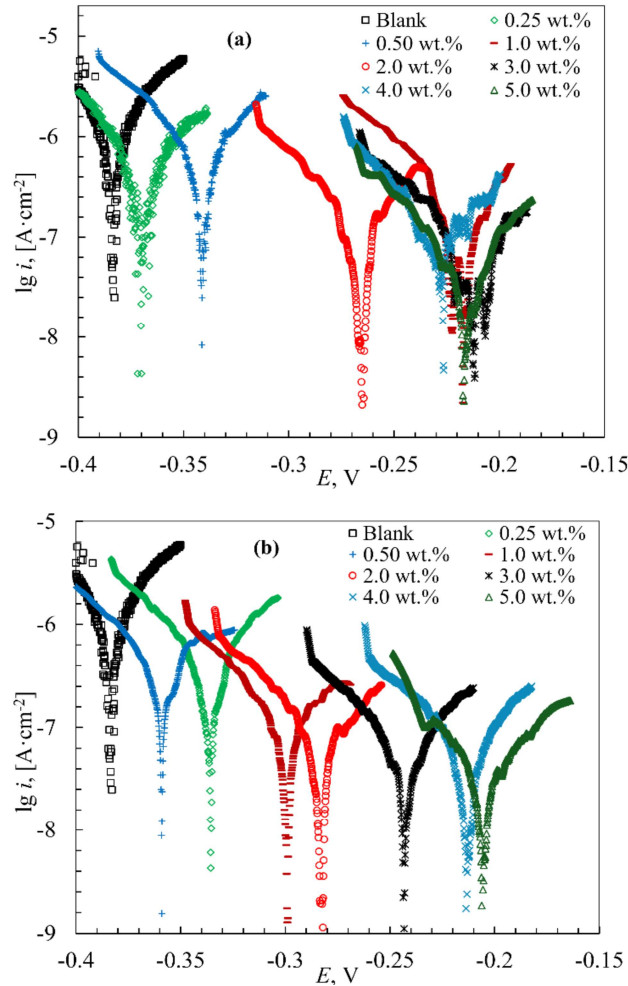


Figure 1. Initial segments of polarization curves of reinforcing steel in concrete pore solution + 3% NaCl with varying concentrations of inhibitors: IFKhAN-80 (a) and MCI-VN (b)

A similar anodic shift in E_{cor} (from 10 to 160 mV) and a decrease in current densities with increasing inhibitor concentration were observed for IFKhAN-80 (Figure 1a). Notably, the polarization curves were nearly identical in the range of $C_{inh} = 3.0$ -5.0 wt.%.

The calculated values of i_{cor} are presented in Table 1. In general, an increase in the inhibition efficiency (Z_{inh}) was observed with increasing concentration of the tested formulations (Table 1). The highest Z_{inh} value of 97.8% for MCI-VN was achieved at $C_{inh} = 5.0$ wt.%, while the maximum for IFKhAN-80 was 96.4%.

Table 1. Corrosion parameters of reinforcing steel in concrete pore solution with 3% NaCl in the presence of inhibitors, calculated using the Mansfeld method

Inhibitor	C_{inh} , wt. %	E_{cor} , V	R_p , $k\Omega \cdot cm^2$	b_a , mV	b_c , mV	B , mV	i_{cor} , $\mu A \cdot cm^{-2}$	Z_{inh} , %
Blank	0.00	-0.382	6.08	34.9	33.3	17.1	2.805	-
IFKhAN-80	0.25	-0.369	16.0	37.4	23.7	14.5	0.907	67.7
	0.50	-0.341	12.8	15.6	16.1	7.9	0.619	77.9
	1.0	-0.217	59.7	18.7	15.5	8.5	0.306	89.1
	2.0	-0.264	66.2	25.5	26.9	13.1	0.198	92.9
	3.0	-0.211	102.4	29.1	28.3	14.3	0.140	95.0
	4.0	-0.226	40.8	29.6	21.7	12.5	0.142	94.4
	5.0	-0.218	125.9	28.3	23.9	12.9	0.102	96.4
MCI-VN	0.25	-0.359	17.8	26.1	23.9	12.5	0.702	75.2
	0.50	-0.335	22.2	22.1	24.7	11.7	0.525	81.3
	1.0	-0.298	62.9	34.3	35.7	17.5	0.278	90.1
	2.0	-0.282	95.6	29.6	23.9	13.2	0.138	95.1
	3.0	-0.243	109.4	29.6	26.1	13.9	0.127	95.5
	4.0	-0.213	142.9	28.9	28.2	14.3	0.100	96.4
	5.0	-0.206	181.4	23.9	21.7	11.4	0.063	97.8

The Nyquist plots in the absence and presence of the inhibitors showed similar shapes, featuring a distorted semicircle with varying diameters and a linear portion at low frequencies (Figure 2). The impedance spectra in the presence of inhibitors

significantly differed from the control experiment at all concentrations. As the inhibitor concentration (C_{inh}) increased for both IFKhAN-80 and MCI-VN, the diameter of the semicircles also increased. The largest radii were observed at $C_{inh} \geq 1.0$ wt.%.

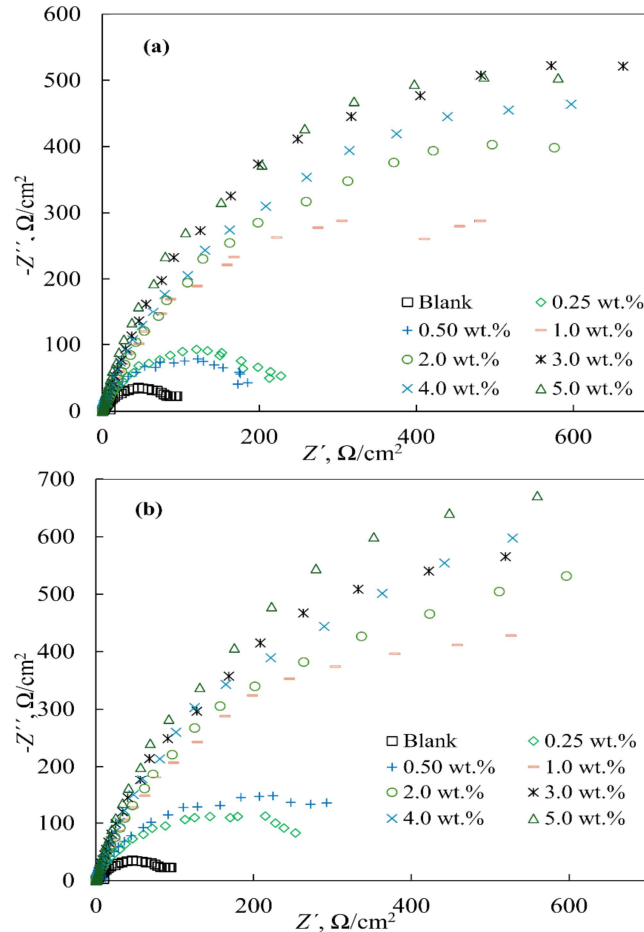


Figure 2. Nyquist plots for reinforcing steel in concrete pore solution with 3% NaCl and varying concentrations of inhibitors: IFKhAN-80 (a) and MCI-VN (b)

The plots are satisfactorily described by the equivalent circuit shown in Figure 3.

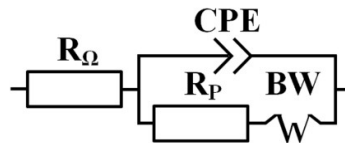


Figure 3. The equivalent circuit used to analyze electrochemical impedance spectra, where R_Ω - solution ohmic resistance, CPE - constant phase element, R_p - polarization resistance of the electrochemical reaction, BW - Warburg impedance.

The calculated values of the equivalent circuit elements are shown in Table 2. At $C_{inh} \geq 1.0$ wt.%, the inhibition efficiencies (η_{inh}) for both tested formulations exceeded 85%.

Table 2. Elements of the equivalent circuit for reinforcing steel in concrete pore solution with 3% NaCl in the presence of inhibitors

Inhibitor	C_{inh} , wt. %	R_{Ω} , $\Omega \cdot \text{cm}^2$	CPE		R_p , $\text{k}\Omega \cdot \text{cm}^2$	BW, $\text{k}\Omega \cdot \text{cm}^2 \cdot \text{s}^{-0.5}$	η_{inh} , %
			Y_0 , $\Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$	n			
Blank	0.00	0.188	0.01328	0.77	95	1.892	—
IFKhAN-80	0.25	0.268	0.00722	0.79	233	3.554	59.3
	0.50	0.174	0.00985	0.83	194	2.626	50.9
	1.0	0.286	0.00863	0.84	717	6.285	86.7
	2.0	0.481	0.00726	0.79	1064	14.962	91.1
	3.0	0.225	0.00682	0.85	1163	43.603	91.8
	4.0	0.141	0.00705	0.85	894	54.822	89.4
	5.0	0.163	0.00883	0.90	1028	45.574	90.8
MCI-VN	0.25	0.194	0.01021	0.83	283	5.297	66.4
	0.50	0.294	0.00971	0.85	313	15.057	69.6
	1.0	0.378	0.0088	0.85	916	34.589	89.6
	2.0	0.119	0.00851	0.85	1252	15.637	92.4
	3.0	0.282	0.00971	0.89	1156	66.82	91.8
	4.0	0.224	0.00932	0.86	1299	55.212	92.7
	5.0	0.052	0.00881	0.89	1285	103.4	92.6

The appearance of the steel specimens at the end of the exposure period is shown in Figure 4. In the control experiment, multiple corrosion defects - such as stains, clusters of pits, and localized corrosion - were observed on the metal surface, visible to the naked eye. No corrosion products or pitting were detected for the IFKhAN-80

inhibitor at $C_{inh} \geq 3.0$ wt.%. At lower concentrations, isolated or grouped pits with diameters up to 3 mm were observed. Adding MCI-VN at $C_{inh} \leq 1.0$ wt.% resulted in forming 1-2 pits with diameters ranging from 3 to 5 mm. With a further increase in concentration to $C_{inh} \geq 2.0$ wt.%, no signs of corrosion damage were detected on the rebar surface, which retained a metallic sheen.

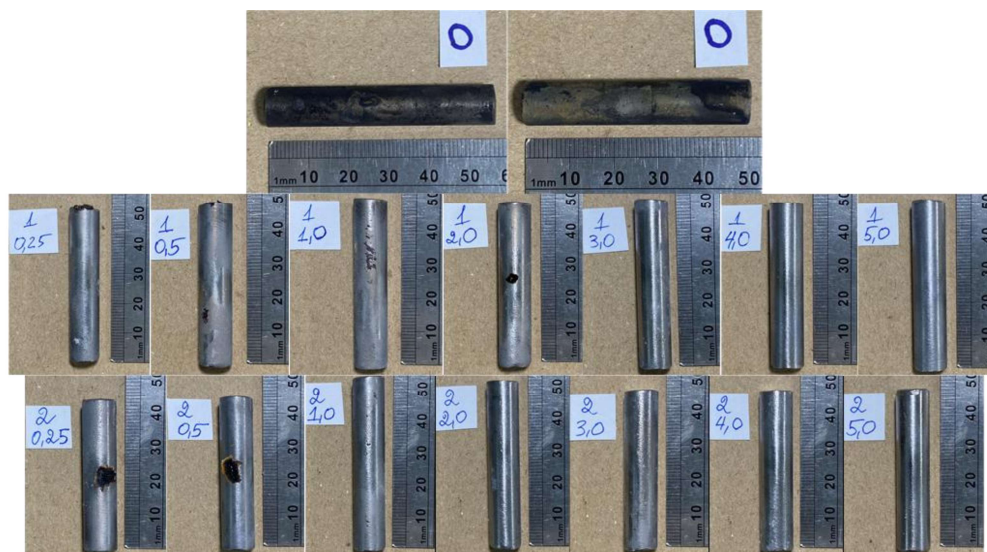


Figure 4. The general appearance of reinforcing steel samples after 30 days of exposure in concrete pore solution with 3% NaCl without inhibitor (0) and with various concentrations of IFKhAN-80 (1) and MCI-VN (2). Inhibitor concentrations (wt.%) are indicated in the images.

The mass loss measurements are shown in Table 3. When the inhibition efficiency based on weight loss (Z_k) exceeded 85%, no pitting or corrosion products were observed on the steel surface. For MCI-VN, this corresponds to $C_{inh} \geq 2.0$ wt.%, whereas for IFKhAN-80, the same result was achieved at $C_{inh} \geq 3.0$ wt.%.

Table 3. Results of gravimetric measurements over 30 days

Inhibitor	C_{inh} , wt.%	k , $\text{g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$	Z_k , %
Blank	0.00	0.446	—
IFKhAN-80	0.25	0.214	51.9
	0.50	0.213	52.2
	1.0	0.141	68.4

Inhibitor	C_{inh} , wt. %	k , $\text{g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$	Z_k , %
	2.0	0.080	82.2
	3.0	0.067	85.1
	4.0	0.043	90.4
	5.0	0.037	91.8
MCI-VN	0.25	0.249	44.2
	0.50	0.176	60.4
	1.0	0.093	79.1
	2.0	0.067	85.1
	3.0	0.060	86.7
	4.0	0.055	87.7
	5.0	0.021	95.3

4. DISCUSSION

The results indicate that MCI-VN and IFKhAN-80 exhibit strong anti-corrosion performance at $C_{inh} \geq 1.0$ -2.0 wt.% concentrations, where Z_{inh} exceeds 90% [1]. The anodic shift in E_{cor} with increasing inhibitor concentration suggests a predominant influence on the anodic partial reaction of steel oxidation [18]. The reduction in current densities in both anodic and cathodic branches of the polarization curves for both inhibitors further supports their effectiveness in mitigating corrosion processes.

The Nyquist plots (Figure 2) and the equivalent circuit analysis (Figure 3, Table 2) confirm that the impedance spectra in the presence of inhibitors significantly differ from the control experiment, with larger semicircle diameters at higher concentrations indicating enhanced corrosion resistance. The inhibition efficiencies (η_{inh}) calculated from impedance spectroscopy align with those from potentiodynamic measurements, reinforcing the reliability of the results. MCI-VN consistently showed η_{inh} values 1-3% higher than IFKhAN-80 at equivalent concentrations.

Visual inspection and mass loss measurements (Figure 4, Table 3) corroborate the electrochemical findings. The absence of corrosion defects at $C_{inh} \geq 2.0$ wt.% for MCI-VN and $C_{inh} \geq 3.0$ wt.% for IFKhAN-80 highlights MCI-VN's superior

performance at lower concentrations. The lack of a clear correlation between the number or size of corrosion defects and inhibitor concentration at lower C_{inh} values suggests that a threshold concentration is necessary for complete corrosion suppression.

Based on single-point measurements of corrosion rate using the polarization resistance method, electrochemical impedance spectroscopy, and long-term mass loss experiments in concrete pore solution with 3% NaCl, it was reliably established that the proposed blended inhibitor MCI-VN exhibits strong inhibitory performance toward reinforcing steel at concentrations of $C_{inh} \geq 2.0$ wt.%. The synergistic combination of inorganic and organic salts with a nonionic surfactant in MCI-VN likely contributes to its enhanced performance compared to IFKhAN-80, particularly at lower concentrations.

5. CONCLUSION

A blended corrosion inhibitor (MCI-VN) was developed and evaluated for protecting reinforcing steel in concrete under chloride exposure. The components of the inhibitor allow it to be used as an admixture in new concrete construction, as a component in repair mortars, or as a surface-applied migrating corrosion inhibitor (MCI) for existing structures. Investigations were carried out in a model pore solution containing 3% NaCl. The high anti-corrosion performance of MCI-VN was demonstrated based on polarization resistance measurements, electrochemical impedance spectroscopy, and gravimetric tests. The highest inhibition efficiency, ranging from 85% to 97% depending on the evaluation method, was achieved at concentrations of $C_{inh} \geq 2.0$ -5.0 wt.%.

Comparison with the commercial inhibitor IFKhAN-80 showed comparable results; however, the efficiency of MCI-VN was up to 3% higher. It was also observed that in the case of MCI-VN, no signs of corrosion were detected on the surface of steel reinforcement after 30 days of exposure at $C_{inh} \geq 2.0$ wt.%, while for IFKhAN-80, a similar outcome was achieved only at $C_{inh} \geq 3.0$ wt.%. These findings suggest that MCI-VN is a promising candidate for enhancing the durability of reinforced concrete structures exposed to chloride environments.

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Conflict of interest statement: *The authors declare that there are no conflicts of interest related to this article.*

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