

An Experimental Study on the Effect of Migratory Corrosion Inhibitors on the Durability of Concrete

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Abstract

The durability of reinforced concrete remains a primary concern in aggressive service conditions, where chloride-induced corrosion of the embedded steel governs the loss of structural service life. Migratory Corrosion Inhibitors (MCIs) offer an attractive route to mitigation because they diffuse through the pore network of hardened concrete and build a protective film on the reinforcement without altering normal construction practice. This work reports an experimental evaluation of four commercial migratory corrosion inhibitors, designated MCI-1 to MCI-4 and their influence on the durability of high-strength concrete. An M50 mix containing fly ash and alccofine as supplementary cementitious materials was adopted as the base matrix and the effect of each inhibitor on transport behaviour was assessed through the water permeability test conducted as per IS 516 (Part 2, Section 1) and the rapid chloride penetration test (RCPT) performed in accordance with ASTM C1202 at 28 days of curing. MCI-1 produced the lowest depth of water penetration, 7.33 mm, about 64% below the control, indicating a denser near-surface pore structure. The RCPT data revealed a different order, with MCI-4 returning the most consistently low charge passed, 1803 coulombs and therefore the strongest control over chloride ion movement. One-way analysis of variance confirmed that the differences among the mixes were statistically significant for both tests ($p < 0.01$) and a Fick's-second-law estimate translated the charge data into service-life differences of several years. These results show that the benefit of an MCI is tied to the transport mechanism that controls deterioration, so the inhibitor must be matched to the expected exposure rather than chosen on a single index.

Keywords: Durability, High Strength Concrete, Migratory Corrosion Inhibitor (MCI), Rapid Chloride Penetration Test (RCPT), Water Permeability.

Introduction

The ability of concrete to withstand its service environment depends strongly on how readily water and dissolved ions move through the material, since a dense matrix with a discontinuous pore system resists moisture and chemical attack far better than an open, permeable one. Performance-based thinking on durability has therefore shifted attention from compressive strength alone towards transport properties (1). In marine and coastal exposure, the problem is sharper still, because chloride, sulphate and magnesium ions promote expansion, cracking and surface delamination and chloride ingress in particular triggers corrosion of the embedded steel (2). Among the available mitigation measures, Migratory Corrosion Inhibitors (MCIs) have gained wide acceptance; these amino-alcohol-based compounds travel through the pore solution of hardened concrete and adsorb onto the steel

surface, where they restore or maintain a passive film. Long-term monitoring of concrete treated with an alkylaminoalcohol inhibitor has shown that the corrosion rate falls when chloride at the steel is not already excessive, improving as more inhibitor reaches the bar (3). Laboratory studies on concrete subjected to controlled chloride erosion confirm that protection is greatest when the inhibitor is present before chloride builds up (4) and field trials on surface-applied inhibitors in a sea wall have reported high inhibition efficiency sustained over several years, even in cracked regions (5). More recent work under coupled salt, freeze-thaw and wet-dry cycling and under combined accelerated carbonation and chloride attack, has demonstrated that amino-alcohol inhibitors reduce concrete porosity and delay the passivation breakdown of the embedded steel (6, 7). The electrochemical basis for inhibitor action

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has been traced to the adsorption of nitrogen- and oxygen-bearing functional groups, which forms a compact molecular film that shifts the pitting potential positively (8). Comparative evaluation of migrating inhibitors used as repair treatments indicates that the concentration reaching the reinforcement and the chemical form of the active species principally determine long-term efficiency (9). Most of this evidence, however, concentrates on the electrochemical response of the steel rather than on how the inhibitor alters the transport properties of the surrounding concrete.

The base concrete itself is the first line of defence and supplementary cementitious materials are routinely used to refine its pore structure. Replacing part of the cement with fly ash tightens the capillary system through pozzolanic reaction and lowers both water and chloride permeability, although the benefit develops gradually as hydration proceeds (10). Ultrafine slag-based additions such as alccofine act similarly at a finer scale, filling voids and improving resistance to chloride movement (11, 12). Ternary fly-ash-alccofine binders can keep chloride permeability in the low band while sustaining high strength (13). A well-graded high-strength matrix built on these materials provides a stable platform on which the effect of an inhibitor can be isolated.

Transport through concrete is governed by the size, connectivity and tortuosity of its pores. Cracking is especially damaging, because even fine cracks form continuous channels that admit water and aggressive species, raising permeability by orders of magnitude (14, 15). Because so many factors influence moisture ingress, no single permeability test has achieved universal acceptance (16). Chloride resistance is most often screened with the rapid chloride penetration test, which records the charge passed under an applied potential; the method is convenient but sensitive to pore-solution chemistry and to the supplementary materials present, so its readings do not always track the true chloride front (17-19) and it commonly shows a coefficient of variation above ten per cent (20). Studies linking pore structure to transport further caution that electrical results should be validated against hydraulic measurements for non-traditional binders (21, 22). Broader durability reviews and service-life frameworks confirm that reliable estimates require accurate determination of the

chloride diffusion coefficient alongside the critical chloride threshold (23, 24).

Despite this extensive electrochemical characterisation of MCIs, their influence on the two transport mechanisms that govern corrosion initiation, namely resistance to pressurised water ingress and resistance to chloride migration, has not been examined comparatively within a single high-strength matrix. Whether an inhibitor that performs well on one mechanism performs equally on the other remains unresolved, which is the gap addressed here.

The present study isolates the contribution of four commercial migratory corrosion inhibitors to these two transport mechanisms in a high-strength M50 matrix. The specific objectives are

- (a) to characterise the four inhibitors physically;
- (b) to quantify their effect on water penetration under pressure (IS 516) and on chloride migration by RCPT (ASTM C1202) at 28 days;
- (c) to test the statistical significance of the differences among the inhibitors; and
- (d) to translate the transport data into an indicative service-life estimate through Fick's second law.

The novelty of the work lies in treating inhibitor selection as a transport-mechanism-matching problem rather than a single-index ranking, supported by replicate-level statistical analysis and a service-life interpretation, so that MCI selection can be placed on a performance basis for a given exposure.

Methodology

Migratory corrosion inhibitors are valued for their ability to penetrate hardened concrete and form protective molecular layers on the embedded steel (3, 4). In this investigation, four commercially available inhibitors, designated MCI-1, MCI-2, MCI-3 and MCI-4, were selected to compare their effect on the durability of high-strength concrete. The choice was based on differences in chemical composition and manufacturer specification, with the aim of assessing relative performance under identical mixing, exposure and testing conditions. Before incorporation into concrete, each inhibitor was characterised physically to confirm consistency, safety and reproducibility, as summarised in Table 1. The properties recorded were visual appearance, odour, potential skin irritation, pH and specific gravity at 25 °C. All four

inhibitors were liquid, gave a mild ammoniacal odour, left no visible residual deposits and caused no skin irritation, which confirmed their suitability for laboratory handling and for mixing into concrete. The pH values ranged from moderately

to highly alkaline, a condition that favours the passivity of the embedded steel. The specific gravity of every sample was close to unity, which ensured uniform dispersion within the matrix without segregation.

Table 1: Physical Analysis of the Four Migratory Corrosion Inhibitors

Inhibitor Sample	Appearance	Odour	Skin Irritation	pH	Specific Gravity
MCI-1	Brownish red liquid, no visible residual deposits	Mild Ammoniacal	No Irritation	11.38	1.01
MCI-2	White liquid, no visible residual deposits	Mild Ammoniacal	No Irritation	12.72	1.00
MCI-3	White liquid, no visible residual deposits	Mild Ammoniacal	No Irritation	12.15	1.00
MCI-4	Pale yellow liquid, no visible residual deposits	Mild Ammoniacal	No Irritation	12.39	1.00

Note: MCI = Migratory Corrosion Inhibitor. pH and specific gravity determined at 25 °C.

An M50-grade concrete was designed as the base matrix for evaluating the influence of the inhibitors. High-strength concrete was chosen deliberately because it is relevant to aggressive exposure such as marine and industrial settings, where chloride ingress and moisture penetration are the critical durability concerns. The complete experimental workflow, from inhibitor characterisation through dosing, casting and testing to statistical evaluation, is shown schematically in Figure 1. The proportions of the control mix and the four inhibitor-modified mixes are given in Table 2.

Figure 1 sets out the complete experimental programme as a single sequence. It begins with the four commercial inhibitors and their physical characterisation, proceeds to the design of the M50 base matrix and the fixed-dosage addition of each inhibitor to the mixing water, and then covers casting, standard water curing and the two durability tests. The final stage links the measured transport behaviour to the statistical evaluation and to the selection of the inhibitor best matched to each exposure, so that every step from raw material to interpretation can be traced within one framework.

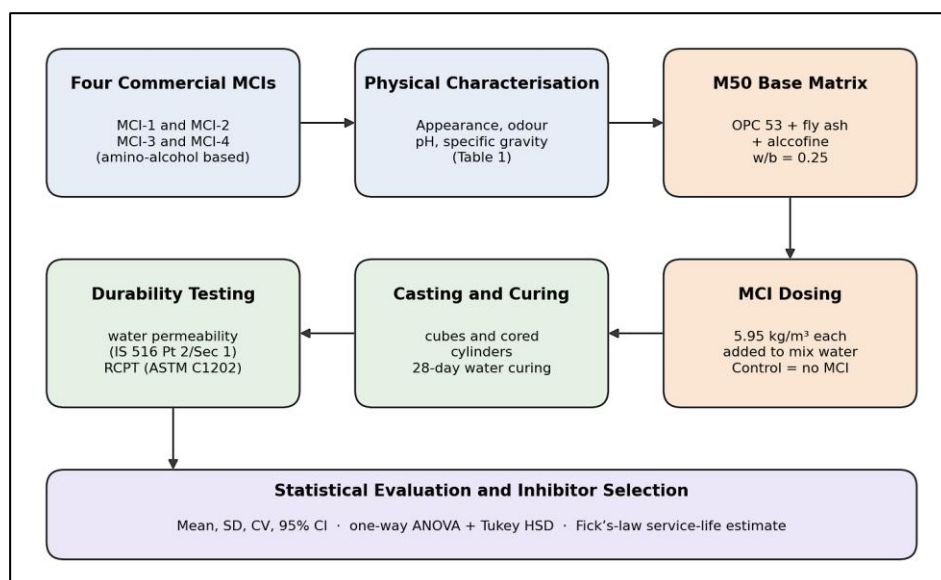


Figure 1: Schematic of the Preparation of the Migratory-corrosion-inhibitor-modified Concrete and the Experimental Programme

Note: MCI = Migratory Corrosion Inhibitor, OPC = Ordinary Portland Cement, w/b = water-to-binder ratio, RCPT = Rapid Chloride Penetration Test, IS = Indian Standard, ASTM = American Society for Testing and Materials, SD = Standard Deviation, CV = Coefficient of Variation, CI = Confidence Interval, ANOVA = Analysis of Variance, HSD = Honestly Significant Difference.

Table 2: Materials Used for the M50 Mix Design (kg/m³)

Mix	Cement (UT OPC 53)	Fly ash	Alccofine	CS-1	10 mm	20 mm	Water	Super-plasticizer	MCI
Control	450	120	25	730	440	560	150	3.57	–
MCI-1	450	120	25	730	440	560	150	3.57	5.95
MCI-2	450	120	25	730	440	560	150	3.57	5.95
MCI-3	450	120	25	730	440	560	150	3.57	5.95
MCI-4	450	120	25	730	440	560	150	3.57	5.95

Note: OPC = Ordinary Portland Cement, CS = Crushed Sand, MCI = Migratory Corrosion Inhibitor. All quantities are expressed in kg/m³; MCI dosage is 1.0% by mass of binder.

The complete mix proportions are summarised in Table 2. The total binder content was 595 kg/m³, comprising 450 kg/m³ of Ordinary Portland Cement (OPC 53), 120 kg/m³ of fly ash (20.2% of the binder) and 25 kg/m³ of alccofine (4.2% of the binder). The water-to-binder ratio was 0.25, with a water content of 150 kg/m³. Crushed sand of 730 kg/m³ formed the fine fraction and coarse aggregate was supplied as 440 kg/m³ of 10 mm and 560 kg/m³ of 20 mm material, giving a fine-to-total aggregate ratio of 0.42. A polycarboxylate-ether superplasticizer was dosed at 3.57 kg/m³ (0.6% of the binder) and each inhibitor was added at a fixed dosage of 5.95 kg/m³ (1.0% of the binder). These proportions were held identical across the control and the four inhibitor-modified mixes, so that any difference in durability could be attributed mainly to the presence and type of MCI. The combined use of fly ash and complementary pozzolanic materials as partial cement replacements is known to reduce porosity and

sorptivity, particularly when the supplementary combination is optimised for particle-size complementarity (25-27) and careful selection of both the binder system and any inhibitor admixture is a prerequisite for adequate service life in coastal exposure (28, 29). A control mix without inhibitor was cast alongside the four modified mixes, each carrying one inhibitor at the fixed dosage, allowing a fair and systematic comparison.

The cement was Ordinary Portland Cement meeting OPC 53-grade requirements and its chemical and physical properties were verified in the laboratory before use against the relevant Indian Standard specifications. The chemical analysis confirmed that the composition satisfied the prescribed limits for the major oxides, loss on ignition, chloride content and magnesium oxide, while the tricalcium silicate and tricalcium aluminate contents lay within acceptable ranges. The results are listed in Table 3.

Table 3: Chemical Test Report of the Cement

Test	Result (%)	Requirement as per IS 269:2015 (Table 2, OPC 53)
Calcium Oxide (CaO)	61.79	–
Silica content (SiO ₂)	19.93	–
Sulphur trioxide (SO ₃)	2.45	3.5 (max.)
Alumina content (Al ₂ O ₃)	5.30	–
Iron content (Fe ₂ O ₃)	4.10	–
Magnesium oxide (MgO)	1.89	6.0 (max.)
Loss on ignition (LOI)	2.50	4.0 (max.)
Insoluble residue	1.44	5.0 (max.)
Chloride (Cl)	0.006	0.1 (max.)
Ratio Al ₂ O ₃ / Fe ₂ O ₃	1.29	0.66 (min.)
Tricalcium aluminate (C ₃ A)	7.12	–
Tricalcium silicate (C ₃ S)	51.56	–
Lime saturation factor	0.93	0.80 to 1.02

Note: LOI = Loss on Ignition, C₃A = Tricalcium Aluminate, C₃S = Tricalcium Silicate, IS = Indian Standard.

The physical tests showed satisfactory fineness, setting times, compressive strength and soundness. The compressive strength at 3, 7 and 28 days exceeded the minimum values for OPC 53 grade, confirming the suitability of the cement for

high-strength concrete. These results, given in Table 4, ensured that the cement quality would not introduce variability and that the observed effects could be linked reliably to the inhibitors.

Table 4: Physical Test Report of the Cement

Physical parameter	Result	Requirement as per IS 269:2015 (Table 3, OPC 53)
Standard consistency (%)	28	–
Specific surface (m^2/kg)	339	225 (min.)
Initial setting time (min)	135	30 (min.)
Final setting time (min)	195	600 (max.)
Compressive strength, 3 days (N/mm^2)	41.5	27.0 (min.)
Compressive strength, 7 days (N/mm^2)	51.0	37.0 (min.)
Compressive strength, 28 days (N/mm^2)	62.5	53.0 (min.)
Soundness, Le-Chatelier (mm)	1	Not more than 10

Note: IS = Indian Standard.

The experimental programme measured the influence of the inhibitors on two durability properties, resistance to water ingress and resistance to chloride ion penetration, which are among the most important factors governing the initiation and propagation of corrosion in reinforced concrete. Water permeability testing assesses the ability of concrete to resist pressurised water and therefore reflects pore connectivity and microstructural integrity, while rapid chloride penetration testing quantifies

resistance to chloride migration. Used together, the two tests give a rounded picture of durability under aggressive conditions.

The transport-and-protection mechanism that underlies inhibitor action is summarized schematically in Figure 2. The inhibitor migrates through the pore solution of the cover concrete, adsorbs on the reinforcing steel and builds a protective molecular film that competes with chloride ions at the steel surface.

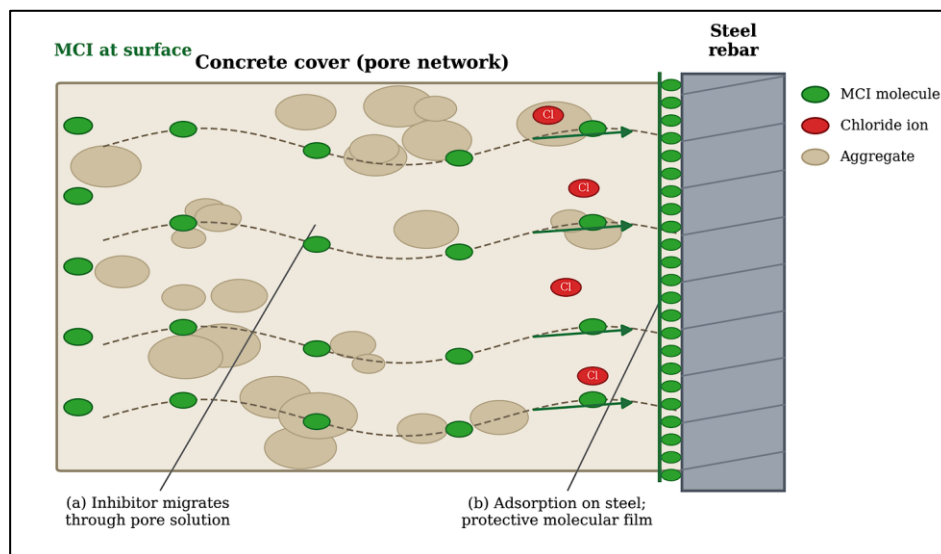


Figure 2: Schematic of the Inhibitor Transport-and-protection mechanism, Showing Migration of the Inhibitor Through the Concrete Pore Network, Adsorption on the Reinforcing Steel and Formation of the Protective Molecular Film That Competes with Chloride Ions

Note: MCI = Migratory Corrosion Inhibitor.

Water permeability testing was carried out in accordance with IS 516 (Part 2, Section 1) after 28 days of standard curing. The face exposed to water pressure was cleaned with a hardened steel brush to remove laitance and ensure uniform contact. Each specimen was placed in a permeability cell with the rough face towards the water inlet; rubber sealing rings provided a watertight fit and grease was applied where necessary to prevent leakage.

All valves were closed before water was introduced gradually and trapped air was released through the vent. A constant pressure of $0.5 \text{ N}/\text{mm}^2$ was applied and held for 72 hours. On completion, each cube was split along a vertical plane in a compression testing machine and the maximum depth of water penetration was measured on the fractured surface to the nearest

millimetre, allowing a direct comparison of the control and the inhibitor-modified concretes.

Rapid chloride penetration testing was performed in accordance with ASTM C1202. Cylindrical core

specimens were conditioned by a standard vacuum-saturation process to give uniform moisture distribution and their sides were sealed so that only the test faces remained exposed.

The total charge passed through a specimen was normalised to a 95 mm diameter using the Equation [1]:

$$Q_s = Q_x \times (3.75 / x)^2 \quad [1]$$

where Q_s is the charge passed through a specimen normalised to 95 mm diameter, Q_x is the charge passed through a specimen of diameter x and x is the actual non-standard diameter in inches.

Each specimen was placed between two chambers, with a sodium chloride solution on the negative side and a sodium hydroxide solution on the positive side. A constant potential difference was applied for six hours; the current was recorded at regular intervals and the total charge passed was calculated in coulombs and used to classify chloride ion penetrability and compare the inhibitors.

Results and Discussion

This section interprets the durability of the control concrete and the four inhibitor-modified concretes through the water permeability test (IS 516 Part 2,

Section 1) and the rapid chloride penetration test (ASTM C1202). The discussion focuses on the comparative trends, the repeatability across replicate specimens, the statistical significance of the differences and the material-level mechanisms that most plausibly explain the observed behaviour.

Table 5 reports the maximum depth of water penetration measured after 72 hours under the applied pressure. A lower penetration depth indicates a denser pore network with reduced capillary connectivity, generally linked to better resistance to moisture transport and improved durability.

Table 5: Observed Depth of Water Penetration

Mix	Water penetration, individual specimens (mm)	Average (mm)
Control	21, 20, 20	20.33
MCI-1	7, 6, 9	7.33
MCI-2	13, 16, 25	18.00
MCI-3	8, 16, 10	11.33
MCI-4	15, 20, 19	18.00

Note: MCI = Migratory Corrosion Inhibitor. Values are the maximum depth of water penetration measured to the nearest millimetre after 72 h under 0.5 N/mm² pressure (n = 3 per mix).

The control concrete recorded penetration depths of 21, 20 and 20 mm, giving an average of 20.33 mm, which sets the baseline permeability of the M50 matrix. Among the modified mixes, MCI-1 achieved the lowest penetration depth, at 7, 6 and 9 mm with an average of 7.33 mm. Relative to the

control this is a reduction of about 64 per cent, a clear improvement in resistance to pressurised water that suggests MCI-1 promoted pore blocking, improved the continuity of the microstructure, or introduced a transport-limiting behaviour in the near-surface zone.

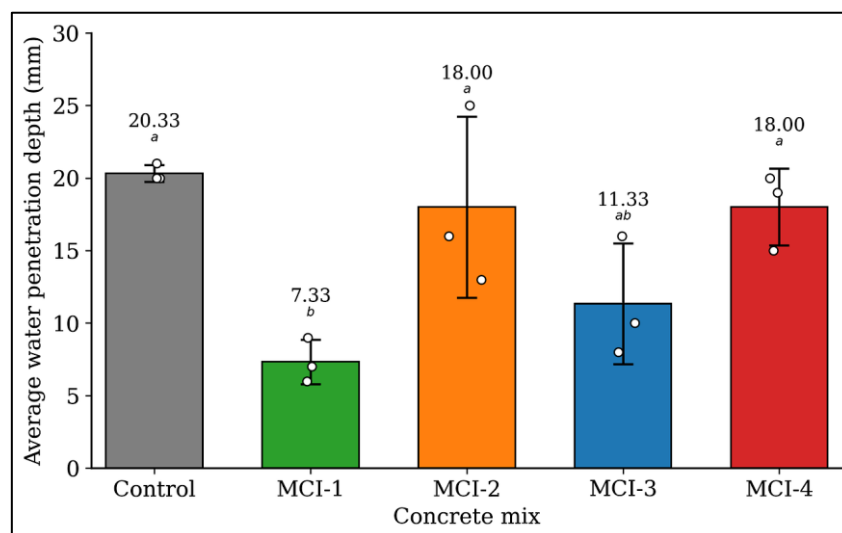


Figure 3: Average Depth of Water Penetration for the Control and the MCI-modified Mixes (Mean of Three Specimens; Error Bars Denote One Standard Deviation; Open Circles Show Individual Replicates; Letters Denote Tukey HSD Groups, Means Sharing a Letter Not Significantly Different at $p < 0.05$)

Note: MCI = Migratory Corrosion Inhibitor, SD = Standard Deviation, HSD = Honestly Significant Difference.

As seen in Figure 3, MCI-3 gave an intermediate but clearly improved result, with depths of 8, 16 and 10 mm and an average of 11.33 mm, a reduction of about 44 per cent compared with the control. Although MCI-3 improved water resistance, its values scattered more widely than those of MCI-1, which implies that its effect is more sensitive to dispersion, curing variability or local heterogeneity in the microstructure. MCI-2 and MCI-4 both averaged 18.00 mm, only about an 11 per cent reduction relative to the control, so under pressurised water these two inhibitors did not change the transport resistance of the matrix to any meaningful extent. The individual replicate values plotted in Figure 3 make the contrast in scatter between the tightly grouped MCI-1 and the widely spread MCI-2 immediately visible.

The repeatability of the results adds further insight. The control scattered little, from 20 to 21 mm and MCI-1 was equally consistent, from 6 to 9 mm, which supports a robust and reproducible effect. MCI-2 showed the widest range, from 13 to 25 mm, pointing to a non-uniform action that may stem from uneven distribution during mixing, sensitivity to local water-to-binder variation, or interaction with the superplasticizer. MCI-4 was moderately variable, from 15 to 20 mm and remained broadly comparable with the control. Water permeability is controlled mainly by pore size distribution, pore continuity and near-surface densification (16). The strong reduction for MCI-1

and to a lesser degree for MCI-3, indicates that these inhibitors contributed to a reduced connectivity of the capillary pores through pore blocking or deposition, a refinement of the interfacial transition zone, or the formation of a transport-limiting film in the near-surface region. This behaviour is consistent with findings from studies on organic corrosion-inhibitor admixtures, which have shown through NMR and SEM analyses that ester- and alcohol-amine-based compounds shift the pore size distribution towards finer pores and reduce the total volume of capillary pores compared with reference concrete (30) and with reports that nitrogen- and oxygen-bearing organic inhibitors produce a more compact interfacial structure that may concurrently reduce local pore connectivity near the reinforcement (31). The present reductions of 44 to 64 per cent are of the same order as the porosity refinement reported in those studies, which supports the pore-refinement interpretation. Water permeability on its own does not confirm chloride resistance, however, because ionic transport also depends on pore-solution chemistry, electrical resistivity and ion mobility, a distinction that becomes clear once the RCPT results are considered.

Table 6 reports the total charge passed over six hours. Using the standard interpretive bands of ASTM C1202, values between 1000 and 2000 coulombs fall in the low category, while 2000 to 4000 coulombs indicate moderate penetrability.

Table 6: Observed Charge Passed in the Rapid Chloride Penetration Test

Mix	Charge passed, individual specimens (coulombs)	Mean (chloride ion penetrability)
Control	1881, 1829, 1666	1792 (Low)
MCI-1	2372, 2184, 1745	2100 (Moderate)
MCI-2	2752, 2804, 2532	2696 (Moderate)
MCI-3	1844, 2179, 2022	2015 (Moderate)
MCI-4	1785, 1919, 1704	1803 (Low)

Note: MCI = Migratory Corrosion Inhibitor. Penetrability class (low or moderate) is assigned according to the ASTM C1202 charge-passed bands (n = 3 per mix)

The control specimens recorded 1881, 1829 and 1666 coulombs, a mean of 1792 coulombs, corresponding to low chloride ion penetrability. This is the expected outcome for a well-designed

high-strength matrix containing supplementary cementitious materials (10, 11). A clear divergence in performance then appeared among the modified mixes, as shown in Figure 4.

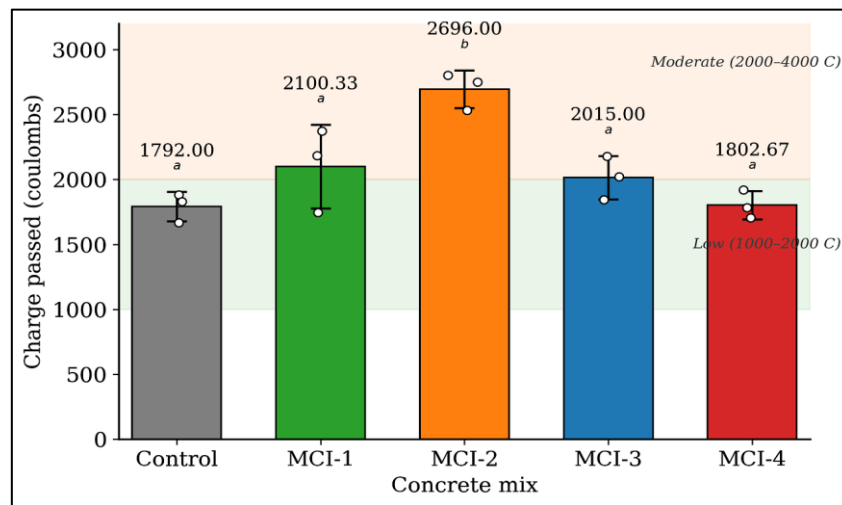


Figure 4: Mean RCPT Charge Passed for the Control and the MCI-Modified Concrete (Mean of Three Specimens; Error Bars Denote One Standard Deviation; Open Circles Show Individual Replicates; Shaded Bands Mark the ASTM C1202 Low and Moderate Ranges; Letters Denote Tukey HSD Groups at $p < 0.05$)
Note: RCPT = Rapid Chloride Penetration Test, MCI = Migratory Corrosion Inhibitor, ASTM = American Society for Testing and Materials, SD = Standard Deviation, HSD = Honestly Significant Difference.

MCI-4 gave the most consistent and favourable RCPT performance, with values of 1785, 1919 and 1704 coulombs and a mean of 1803 coulombs. All three specimens fall in the low-penetrability band and the average is essentially the same as the control, showing that MCI-4 did not compromise chloride resistance and may help sustain low ionic transport across the matrix, which is particularly valuable in chloride-exposed environments (2). MCI-2 was the least favourable, with 2752, 2804 and 2532 coulombs and a mean of 2696 coulombs, classified consistently as moderate. Relative to the control mean the charge passed rose by about 50 per cent, indicating substantially higher ionic transport under the applied field. This result shows that an inhibitor can appear acceptable for one transport mechanism, here water penetration,

while performing poorly for another, here ionic migration.

MCI-1 produced a mixed response, with two specimens in the moderate range (2372 and 2184 coulombs) and one in the low range (1745 coulombs), giving a mean of 2100 coulombs. This points to variable control of ionic transport that may arise from uneven inhibitor distribution, sensitivity to local pore-solution conductivity, or differences in moisture conditioning between specimens, which strongly affects RCPT readings (17, 19). MCI-3 behaved similarly, with one low value (1844 coulombs) and two moderate values (2179 and 2022 coulombs), a mean of 2015 coulombs, placing its average at the boundary between low and moderate penetrability.

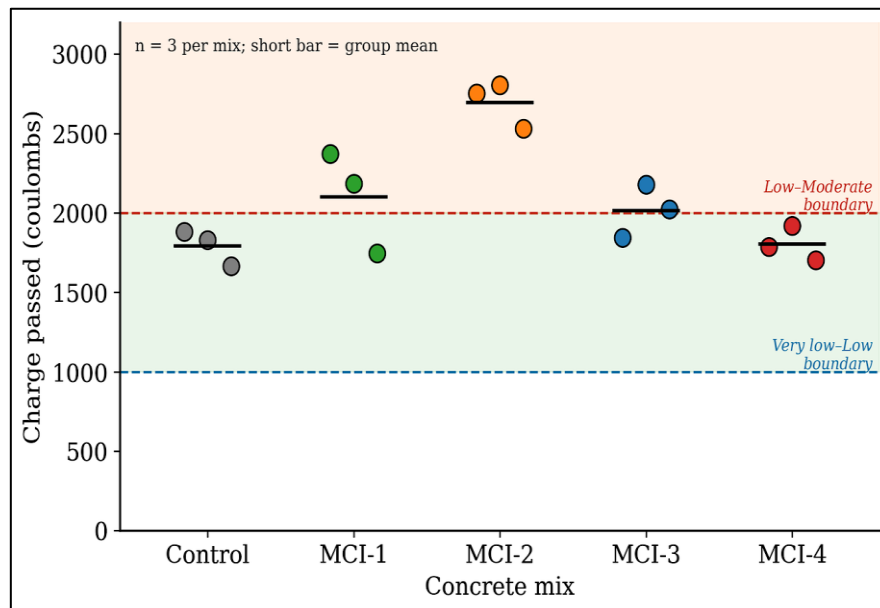


Figure 5: Charge Passed Per Specimen in the RCPT Showing Replicate Variability Against the ASTM C1202 Classification Boundaries (N = 3 Per Mix; Short Horizontal Bar Denotes the Group Mean)

Note: RCPT = Rapid Chloride Penetration Test, ASTM = American Society for Testing and Materials.

Figure 5 brings together the individual specimen values for all five mixes and overlays the ASTM C1202 classification boundaries, making it straightforward to see which mixes straddle the low-to-moderate threshold and which remain consistently within a single band.

Statistical Analysis

To establish whether the differences among the mixes were statistically significant rather than a product of specimen-to-specimen scatter, the triplicate results of each test were analysed. The mean, standard deviation (SD), coefficient of variation (CV) and 95% confidence interval (CI) of every mix are reported in Table 7. The water penetration results showed low scatter for the control (CV 2.8%) but wide scatter for MCI-2 (CV 34.7%) and MCI-3 (CV 36.7%), while the RCPT

results were tighter overall, with CV values between 5.4% and 15.3%. A one-way analysis of variance (ANOVA) confirmed that the mix had a significant effect on both water penetration, $F(4,10) = 6.74$, $p = 0.007$ and charge passed, $F(4,10) = 11.53$, $p < 0.001$, with large effect sizes ($\eta^2 = 0.73$ and 0.82 respectively). The pairwise Tukey HSD comparisons summarised in Table 8 show that the reduction in water penetration for MCI-1 was significant against the control, MCI-2 and MCI-4 ($p < 0.05$), whereas for the RCPT the only mix that differed significantly from all others was MCI-2 ($p < 0.05$ in every pairwise comparison). These results confirm that the superior water resistance of MCI-1 and the elevated chloride transport of MCI-2 are statistically robust and not artefacts of variability.

Table 7: Descriptive Statistics for the Water Permeability and RCPT Results (n = 3 per mix)

Test	Mix	Mean	SD	CV (%)	95% CI
Water penetration (mm)	Control	20.33	0.58	2.8	18.90–21.77
	MCI-1	7.33	1.53	20.8	3.54–11.13
	MCI-2	18.00	6.24	34.7	2.49–33.51
	MCI-3	11.33	4.16	36.7	0.99–21.68
	MCI-4	18.00	2.65	14.7	11.43–24.57
RCPT charge (coulombs)	Control	1792	112	6.3	1513–2071
	MCI-1	2100	322	15.3	1301–2900
	MCI-2	2696	144	5.4	2337–3055
	MCI-3	2015	168	8.3	1599–2431
	MCI-4	1803	109	6.0	1533–2072

Note: SD = Standard Deviation, CV = Coefficient of Variation, CI = Confidence Interval, RCPT = Rapid Chloride Penetration Test, MCI = Migratory Corrosion Inhibitor, n = Number of Replicate Specimens per Mix.

Table 8: One-way ANOVA and Significant Tukey HSD Pairwise Differences ($p < 0.05$)

Response	ANOVA F (p)	η^2	Significantly different pairs
Water penetration	6.74 (0.007)	0.73	Control-MCI-1; MCI-1-MCI-2; MCI-1-MCI-4
RCPT charge	11.53 (<0.001)	0.82	Control-MCI-2; MCI-1-MCI-2; MCI-2-MCI-3; MCI-2-MCI-4

Note: ANOVA = Analysis of Variance, F = Variance Ratio, p = Significance Probability, η^2 = eta-squared Effect Size; HSD = Honestly Significant Difference, RCPT = Rapid Chloride Penetration Test, MCI = Migratory Corrosion Inhibitor.

A central outcome of the study is that water permeability and chloride migration resistance, as measured by RCPT, are not necessarily correlated. Two distinct behavioural groups emerged. MCI-1 and MCI-3 mainly improved resistance to water ingress, shown by the large reduction in penetration depth, whereas MCI-4 was superior in controlling chloride migration, returning consis-

tently low RCPT values comparable with the control. This divergence confirms that migratory corrosion inhibitors can influence different transport mechanisms in different ways, so their selection should follow the dominant exposure condition and durability requirement rather than a single test.

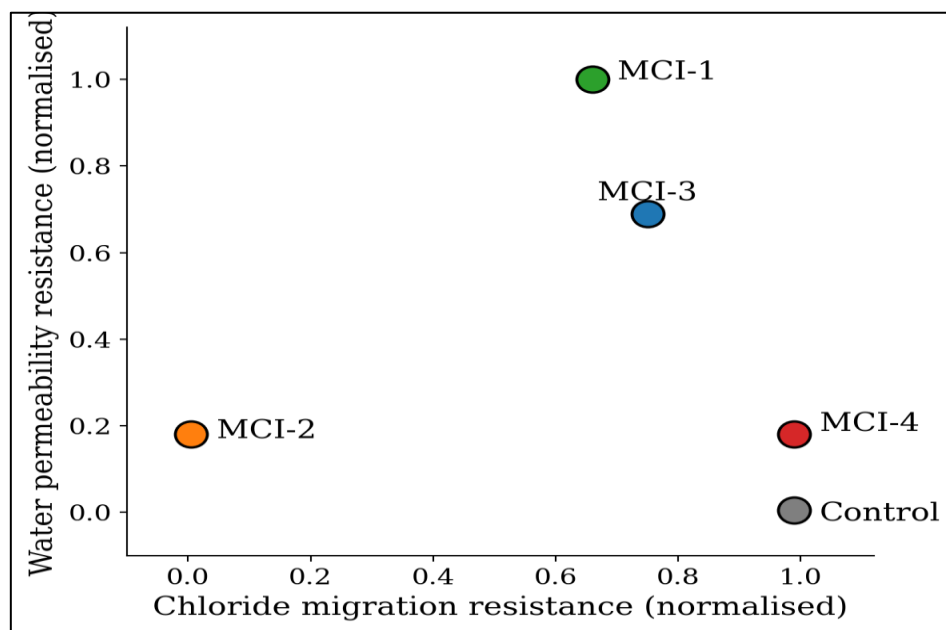


Figure 6: Normalised Durability Performance of the Five Mixes on the Two Transport Mechanisms, Illustrating the Trade-off Between Water Permeability Resistance and Chloride Migration Resistance

Note: MCI = Migratory Corrosion Inhibitor. Positions are normalised (0 to 1) within each transport mechanism across the five mixes.

Figure 6 presents this divergence in normalised form, where the position of each mix reflects how well it addresses each transport mechanism. The clear separation between MCI-1, which occupies the high-water-resistance region and MCI-4, which occupies the high-chloride-resistance region, confirms that no single inhibitor dominates on both criteria simultaneously.

The behaviour of MCI-2 is especially instructive. Despite only a marginal reduction in water penetration depth, it produced consistently higher charge passes. Because RCPT is fundamentally an electrical migration measurement, any change that

increases ionic conductivity, such as altered pore-solution chemistry or a greater supply of mobile ions, can raise the coulomb value without a significant increase in physical pore size (17).

Service-life Estimation Using Fick's Second Law

Because the study is framed around service-life extension, the RCPT charge was translated into an indicative time to corrosion initiation using the one-dimensional solution of Fick's second law, as given in Equation [2]:

$$C(x,t) = C_s [1 - \operatorname{erf}(x / (2\sqrt{D \cdot t}))] \quad [2]$$

where C_s is the surface chloride content, C_{cr} the critical chloride threshold, x the cover depth and D the apparent chloride diffusion coefficient.

Following the empirical relation of Berke and Hicks, in which $D \text{ (cm}^2/\text{s)} = 0.0103 \times 10^{-8} \times Q^{0.84}$ with Q the charge passed in coulombs (32), the mean RCPT values give diffusion coefficients ranging from $5.57 \times 10^{-12} \text{ m}^2/\text{s}$ for the control to $7.85 \times 10^{-12} \text{ m}^2/\text{s}$ for MCI-2. Adopting representative marine-exposure values of 50 mm cover, $C_s = 0.65\%$ and $C_{cr} = 0.40\%$ by mass of binder, the corresponding times to corrosion initiation are listed in Table 9. The estimate places the control and MCI-4 at about 28 years, MCI-1 and

MCI-3 at 25 to 26 years and MCI-2 at only 20 years, an eight-year reduction relative to the control that is consistent with its elevated charge passed. The Berke and Hicks correlation is acknowledged to lose accuracy above roughly 2000 coulombs (32), so these figures are indicative rather than absolute; they are presented to illustrate the practical consequence of the measured transport differences rather than to predict field service life precisely.

Table 9: Indicative Apparent Chloride Diffusion Coefficient and Time to Corrosion Initiation Estimated from the Mean RCPT Charge (50 mm cover; $C_s = 0.65\%$, $C_{cr} = 0.40\%$ by mass of binder)

Mix	Mean charge (coulombs)	D ($\times 10^{-12} \text{ m}^2/\text{s}$)	Time to initiation (years)
Control	1792	5.57	28.2
MCI-1	2100	6.36	24.7
MCI-2	2696	7.85	20.0
MCI-3	2015	6.14	25.5
MCI-4	1803	5.60	28.0

Note: D = Apparent Chloride Diffusion Coefficient, C_s = Surface Chloride Content, C_{cr} = Critical Chloride Threshold, RCPT = Rapid Chloride Penetration Test, MCI = Migratory Corrosion Inhibitor.

From a practical standpoint the suitability of an inhibitor is strongly governed by the dominant transport mechanism and the exposure environment. Where water-driven transport and general moisture ingress are the main concerns, such as structures subjected to frequent wetting, hydraulic pressure or moisture-induced deterioration, MCI-1 is the most advantageous because of its strong and consistent reduction in water penetration. Where chloride exposure governs durability, including marine splash zones, coastal infrastructure and pavements exposed to de-icing salts, MCI-4 is the most appropriate choice owing to its consistently low chloride penetrability (5).

This conclusion is reinforced by service-life studies of coastal structures, which show that even a modest reduction in the effective chloride diffusion coefficient can extend corrosion-free life by decades when combined with adequate cover (33) and by field observations that structures in tidal and splash positions accumulate chloride at the reinforcement substantially faster than those in mildly exposed positions (34). Ultra-high-performance concrete studies further show that the chloride diffusion coefficient inferred from the charge passed can vary by more than an order of

magnitude with the water-to-cementitious ratio, underlining the value of coupling test results with diffusion-based interpretation rather than the coulomb classification alone (32), while field data from coastal soda-residue environments confirm that transport-oriented inhibitor strategies targeting pore connectivity are more effective than electrochemical ones where high ionic concentration combines with wetting and drying (35). Translating these laboratory findings to the field nonetheless requires caution, since real structures experience combined and cyclic actions that the present saturated, single-age tests do not reproduce.

Limitations of the Study

Several methodological limitations should be acknowledged when interpreting these results. First, each measurement rests on three replicate specimens; while this is sufficient to establish statistical significance through ANOVA, it constrains the precision of the confidence intervals, particularly for the more variable MCI-2 and MCI-3 water penetration data. Second, each inhibitor was assessed at a single dosage of 1.0% of the binder, at a single curing age of 28 days and in a single M50 matrix, so dosage-response, age-

dependent and grade-dependent effects were not explored. Third, the inhibitors are proprietary commercial products whose exact chemistry is not disclosed, which limits mechanistic attribution. Fourth, the two transport tests are indirect: the RCPT is an accelerated electrical-migration measurement that is sensitive to pore-solution conductivity and does not measure true diffusion and the water permeability test records only the depth of penetration under a fixed pressure, not a permeability coefficient.

More importantly, the conclusion that service environment governs inhibitor selection is drawn from controlled laboratory transport tests rather than from environmental simulations. Marine immersion, cyclic wetting and drying, chloride ponding, freeze-thaw and carbonation exposures were not conducted, so the results reflect saturated transport under controlled conditions and cannot capture the coupled, time-dependent deterioration that governs field performance. The service-life estimate in Table 9 likewise depends on an empirical charge-to-diffusion correlation and on assumed exposure parameters and should be read as an illustrative comparison rather than a prediction. Future work should therefore include long-term ponding and natural-diffusion tests, multiple dosages and curing ages, direct electrochemical corrosion monitoring of embedded steel and field or simulated-exposure validation, so that the transport-based ranking established here can be confirmed under realistic service conditions.

Conclusion

This study set out to establish whether four commercial migratory corrosion inhibitors act on the two transport mechanisms that govern chloride-induced corrosion in the same way, using one high-strength M50 matrix so that the inhibitor remained the only variable. Pressurised water permeability testing was paired with the rapid chloride penetration test, and both were supported by replicate-level statistics and a Fick's-second-law service-life interpretation. The value of the work lies in treating inhibitor selection as a transport-mechanism-matching problem rather than a single-index ranking, which moves the basis for choosing an inhibitor from a general expectation of benefit towards a measured and exposure-specific decision.

The measured behaviour supports this framing. MCI-1 produced the largest and most repeatable reduction in water penetration, about 64 per cent below the control, most plausibly through reduced capillary connectivity and near-surface refinement, while MCI-3 improved water resistance with wider scatter and MCI-2 and MCI-4 changed it only marginally. The chloride results reordered this ranking. MCI-4 held the charge passed at 1803 coulombs, essentially matching the control and remaining in the low-penetrability band, whereas MCI-2 rose to 2696 coulombs and moved into the moderate band. One-way ANOVA confirmed that the differences were significant for both tests ($p < 0.01$), and the service-life estimate translated the charge data into a spread of about eight years between the best and worst performing inhibitors.

For practice, these outcomes mean that an inhibitor cannot be judged from a single durability index. Where moisture ingress and hydraulic pressure dominate, such as water-retaining structures and elements subject to frequent wetting, MCI-1 is the stronger choice. Where chloride governs, including marine splash zones, coastal infrastructure and pavements exposed to de-icing salts, MCI-4 is more appropriate. The wider implication is that a performance-based specification written around the dominant exposure of a given structure will use these products more reliably than a specification built on a single acceptance test.

These conclusions rest on saturated, single-age transport tests carried out on three replicates at one dosage in a single concrete grade, and on an empirical charge-to-diffusion correlation that loses accuracy at higher charge, so they should be read as a controlled transport-based ranking rather than a prediction of field service life. Work that would strengthen and extend the ranking includes long-term ponding and natural-diffusion measurements, several dosages and curing ages, direct electrochemical monitoring of embedded steel, and validation under simulated marine, wetting and drying, carbonation and freeze-thaw exposure. Confirming the present ranking under those coupled conditions would allow migratory corrosion inhibitors to be specified with confidence on a genuinely performance-based footing.

Abbreviations

ANOVA: Analysis of Variance, ASTM: American Society for Testing and Materials, CI: Confidence Interval, CV: Coefficient of Variation, IS: Indian Standard, MCI: Migratory Corrosion Inhibitor, OPC: Ordinary Portland Cement, RCPT: Rapid Chloride Penetration Test, SCM: Supplementary Cementitious Material, SD: Standard Deviation.

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Author Contributions

Shubhra Dagwal: Conceptualization, Methodology Development, Material Characterization and Testing, Investigation, Data Curation, Results Formulation, Visualization, Writing of the Original Draft, Manuscript Revision and Editing, Rajendra B Magar: Supervision, Validation of Results, Resource Provision, Critical Review and Editing, Project administration.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The experimental data, test records and supporting materials generated during this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that generative AI and AI-assisted technologies were used during the preparation of this revised manuscript. AI-assisted tools were used to support language editing and readability, to assist with the statistical analysis and its presentation and to generate the schematic and data figures (Figures 1 to 6) from the authors' own experimental data. All experimental work, measured data, interpretations and conclusions are those of the authors, who reviewed and verified all AI-assisted output and take full responsibility for the content of the manuscript.

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Ethics Approval

Not applicable. This study is based entirely on laboratory experimentation and material testing. No human participants, animal experiments or biological materials were involved.

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