International Journal of GEOMATE, Nov., 2025 Vol.29, Issue 135, pp.50-57
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.135.5100
Geotechnique, Construction Materials and Environment

CHLORIDE DIFFUSION RATE IN LOADED FLY ASH CONCRETE USING STEADY-STATE MIGRATION TEST

Sri Murti Adiyastuti[1], Kemal Pramayuda[1], *Eko Charnius Ilman[1]

[1]Ocean Engineering Program, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Indonesia

*Corresponding Author, Received: 25 June 2025, Revised: 06 Aug. 2025, Accepted: 18 Aug. 2025

ABSTRACT: Chloride-induced corrosion is a major durability concern for concrete structures in marine environments, particularly under mechanical loading, as the resulting micro-cracking and cracking can accelerate chloride ingress, allowing these corrosive ions to reach the steel reinforcement more easily and compromise the structure's integrity. This study investigates the combined effect of mechanical pre-loading and fly ash replacement (0%, 20%, 30%, and 40%) on chloride diffusion in high-strength concrete. Sixteen concrete discs were tested using the NT Build 355 steady-state migration method for durations of 7 and 14 days. Before testing, a load of up to 2,000 kilograms was applied to eight specimens, while the remaining eight were left unloaded. The chloride diffusion coefficient was calculated using the Nernst-Planck equation. The results demonstrated that increasing fly ash content consistently reduced chloride ingress, with a maximum reduction of 79.8% observed in specimens with 40% fly ash under pre-loading conditions. These reductions were repeatable across both durations and fly ash percentages, with notably greater performance observed at 30% and 40% replacement compared to 20%. Replacing cement with 30–40% fly ash significantly enhances the durability and extends the service life of concrete structures in marine environments, even when subjected to pre-loading. Additionally, this approach contributes to sustainability by reducing cement consumption, which in turn lowers carbon dioxide emissions.

Keywords: Chloride, Fly ash, Diffusion, Chloride concentration, Concrete

1. INTRODUCTION

For structural applications, reinforced concrete is considered a robust and durable material. However, steel reinforcement remains susceptible to corrosion and cracking [1]. The initiation of steel corrosion typically triggers concrete degradation, compromising the structural integrity of the concrete. Chloride ions cause damage to the protective passive layer of steel reinforcement. While several factors contribute to steel corrosion in concrete, exposure to seawater remains the dominant cause in marine structures.

The susceptibility of steel reinforcements to corrosion in marine environments increases due to the presence of chloride ions in seawater. The coefficient of chloride diffusion is used to determine the ability of chloride ions to penetrate reinforced concrete. The chloride diffusion coefficient has been investigated in numerous studies [1-12]

Djerbi et al. investigated the impact of fractures in concrete on chloride diffusion. Through a controlled experiment, fine crack widths ranging from 30 to 250 micrometers were measured. The findings indicated that ordinary concrete exhibits wider fractures compared to high-performance concrete. Moreover, due to the inclusion of silica fume in high-performance concrete, its chloride diffusion coefficient is lower than that of ordinary concrete [2]. More recent studies continue to affirm that the pozzolanic reaction of fly ash leads to a densification of the concrete microstructure, significantly reducing porosity and enhancing resistance to chloride ingress over the long term [13]. Cuong showed that replacing 50–60% of cement with fly ash in self-compacting concrete reduced chloride permeability by over 80% at 28 days and 90% at 90 days, highlighting its effectiveness in improving durability for marine structures [14].

Aldea et al. investigated the impact of cracks in concrete on water and chloride permeability. Tests were conducted on both standard and high-strength concrete, with controlled fracturing applied. Additionally, a rapid chloride permeability test (RCPT) is also analyzed, which records the total current during testing. The findings revealed that the total current rises with increasing crack widths. This suggests that as crack widths widen, the chloride diffusion coefficient also increases [3].

Sugiyama et al. explored the chloride diffusion coefficient in concrete and its correlation with gas permeability. Both standard and lightweight concrete were used for this investigation. Through an accelerated test for chloride permeability, the chloride diffusion coefficient was determined. The findings showed that lightweight concrete has a relatively higher chloride diffusion coefficient compared to standard concrete [4].

Heirman et al. studied chloride penetration using migration tests under both steady and non-steady conditions [5]. The procedure outlined in NT Build 355 was employed for the steady-state migration test. The coefficient of chloride diffusion was determined through this steady-state migration test. The findings suggested that the steady-state migration test duration increases with the improvement in the concrete's quality [6].

Kosior-Kazberuk et al. examined the progress of compressive strength in concrete containing fly ash, revealing that after 180 days, concrete with 20% fly ash will exhibit a higher compressive strength compared to concrete without fly ash [7]. Elsageer et al. investigated the increase in compressive strength of fly ash-blended concrete at various curing temperatures, ranging from 10°C to 50°C. Fly ash replaced 15%, 30%, and 45% of the cement in each concrete specimen. After 128 days, the inclusion of fly ash was found to increase compressive strength values under all curing temperature conditions [8].

Pane et al. have demonstrated good compressive strength when activated by sodium hydroxide (NaOH), with optimal results achieved at a 12 M molarity concentration. Although promising, these materials still require further development to meet conventional design performance under ambient conditions [11].

Wang et al. evaluated the impact of adding fly ash on compressive strength using a hydration model for mixtures of cement and fly ash. They found that concrete specimens containing either 15% or 25% fly ash did not surpass the control specimens at an early stage of development. However, at a later stage, the fly ash-blended concrete could outperform the control samples. Conversely, concrete with high concentrations of fly ash, specifically 45% and 55%, could not surpass the control specimens throughout the modelling process [9]. In summary, based on studies [1], [7], [8], [9], [11], the addition of fly ash to concrete mixes increases the compressive strength of concrete specimens. Furthermore, the role of fly ash in chloride binding, the process of immobilizing free chloride ions within the cementitious matrix, is now recognized as a key mechanism for improving durability in marine environments [15].

Recent findings by Ma et al. examined the long-term chloride resistance of alkali-activated fly ash/slag (AAFS) concrete using diffusion and migration tests. AAFS concrete generally showed lower chloride diffusivity than OPC, though high slag content or low w/b ratios may cause shrinkage-induced microcracks. Chloride binding was mainly physical, and the test method choice significantly affected the measured diffusivity [16].

This paper investigates the rate of chloride diffusion in pre-loaded (and hence cracked) concrete as well as mixed fly ash concrete. Fly ash is integrated into the production of high-performance K-400-grade concrete. It serves as a pozzolanic material that can substitute for cement while possessing similar properties. The study assesses the rate of chloride diffusion through a steady-state migration test.

While several studies have explored the impact of cracks or fly ash alone on chloride diffusion, few have quantitatively assessed diffusion behavior in concrete exposed to pre-mechanical loading and various percentages of fly ash replacement.

2. RESEARCH SIGNIFICANCE

This experiment aims to evaluate the impact of pre-loaded concrete containing different percentages of fly ash on the chloride diffusion rate within concrete. The study provides additional insights that may support the assessment of durability in concrete structures, particularly those incorporating fly ash. The findings indicate that the service life of concrete structures is influenced by chloride penetration into the reinforcement. In addition, the use of fly ash contributes to sustainability by reducing cement consumption and associated carbon dioxide emissions, aligning with global efforts to lower the environmental footprint of construction materials.

3. EXPERIMENTAL

Concrete specimens were prepared using cement, aggregates, and fly ash collected from suppliers in West Java, Indonesia. Fly ash, on the other hand, was acquired from PT. Cirebon Power, a Company located in Cirebon, West Java, Indonesia. Four high-performance concrete mixtures with 0%–40% fly ash were cast. The concrete mixing process is summarized in Table 1.

Table 1. Concrete mix proportions (kg per 1 m³ of concrete). Mix types: A = K-400; B = +20% Fly Ash; C = +30% Fly Ash; D = +40% Fly Ash

Component(*)	A	B	C	D
Cement	1.25	0.994	0.875	0.749
Fly Ash	0	0.250	0.375	0.499
Water	0.498	0.498	0.498	0.498
Coarse Aggregate	1.699	1.699	1.699	1.699
Fine Aggregate	2.028	2.028	2.028	2.028
Superplas-ticizer	0.0008	0.005	0.005	0.004

(*) Mix types: A = K-400; B = +20% Fly Ash; C = +30% Fly Ash; D = +40% Fly Ash.

The concrete mix design uses coarse aggregate with a maximum size of 2 cm and water-to-cement ratio of 0.377, indicating a relatively low water content compared to cement. Material properties were tested to determine appropriate mix proportions. After calculating the concrete mixtures, cylindrical concrete specimens were fabricated according to the Indonesian National Standard. Once cylindrical concrete specimens are obtained, the compressive strengths are evaluated at 4, 7, 14, and 28 days. The cylindrical concrete specimens were then cured in the $Ca(OH)_2$ solution before further testing. Subsequently, 50 mm-thick concrete discs are cut from cylindrical specimens. Before testing, a load of up to 2,000 kilograms was applied using a universal testing machine for these eight specimens. Then, throughout the 7- or 14-day migration, tests are performed.

Fig.1 illustrates the NT Build 355 steady-state migration test setup, where a cylindrical concrete specimen is placed between two compartments containing NaCl and NaOH solutions. Electrodes are inserted in each compartment and connected to a direct current power supply to drive chloride ions through the specimen for diffusion measurement. The steady-state migration test measures the quantity of chloride ions that traverse the concrete per unit time. Chloride ions migrate from the first compartment, which contains NaCl (51.7 g/L), to the second compartment, containing NaOH (12 g/L). A constant voltage of 12 V DC is applied by connecting the power supply to both compartments. During testing, the temperature of the samples in both compartments must not exceed 40°C. Every 12 hours, samples are taken from the second compartment and analyzed to determine the chloride concentration.

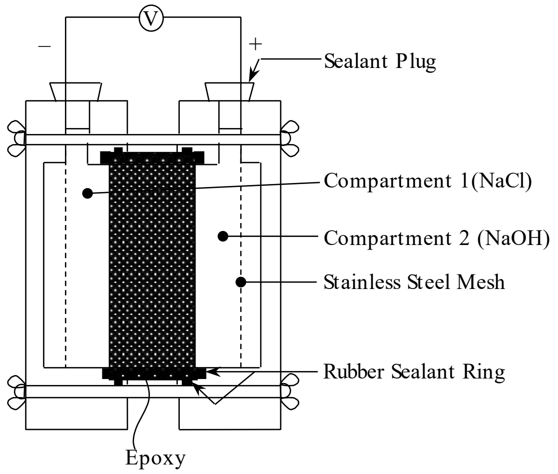

Fig. 1 NT Build 355 steady-state migration test (adopted from [6])

The steady-state migration test employs the Nernst-Planck equation, as shown in Eq. (1), to determine the coefficient of chloride diffusion:

$$J(x) = -D_e \frac{\partial c}{\partial x} + D_e \frac{zFE}{RTL} c + cv(x) \quad (1)$$

where $J(x)$ is the chloride ions flux, in kg/m^{2}s, c is the concentration of chloride in the first compartment, in kg m^{-3}, D_e is the coefficient of chloride diffusion, in m^2 s^{-1}, z is valency of chloride ion (z = 1), F is faraday constant, equal to 6480 J V^{-1} mol^{-1}), E is voltage drop across specimens, in V, R is gas constant, equal to 8.3144 J mol^{-1} K^{-1}, T is temperature, in K, L is sample thickness, in m, and $v(x)$ is the velocity of the solution, in m s^{-1}.

In Eq. (1), the convective flux term $cv(x)$ represents ion transport via bulk pore solution flow. Since the specimens were fully saturated and no hydraulic gradient was applied (Fig. 1), convection is negligible. Chloride transport is primarily driven by diffusion (resulting from concentration gradients) and migration (in response to the applied electric field). Thus, setting solution velocity $v(x)$ = 0 is a valid simplification, leading to the reduced form in Eq. (2) [6].

$$D_e = \frac{LRT}{czFE} J \quad (2)$$

During the experiment, the chloride concentration will increase constantly; therefore, flux J can be calculated by using Eq. (3):

$$J = \frac{V}{A} \frac{\Delta C_{cl^-}}{t} \quad (3)$$

where V is the volume of solution within the second compartment, in m^3, and A is the area of concrete, in m^2. ΔC_{cl^-} is the increased concentration of chloride in the second compartment, and t is the testing period, in seconds.

4. RESULTS AND DISCUSSION

After obtaining cylindrical concrete specimens, the compressive strength will be assessed at 4, 7, 14, and 28 days. Results show that, in these early ages, fly ash (FA) concretes have a relatively lower compressive strength compared to concrete containing no fly ash materials (Fig. 2).

In $Ca(OH)_2$ solutions, cylindrical concrete specimens are cured for 233 days, and the weight gain is determined. Two cylindrical specimens of concrete are sliced into 350 mm-thick concrete discs. The selected cylindrical concrete specimens are shown in Table 2.

The concrete discs are shown in Fig. 3. Eight concrete discs were subjected to a 2,000 kg load using a universal testing machine (Fig. 4). Additionally, eight non-loaded concrete discs were employed as a control variable.

Table 2. Selected cylindrical concrete specimens with the percentage of added weight

Concrete Mix	Concrete Weight (gram)		Added Weight (%)
	Day 1	Day 233	
K-400	3617	3618	0.03
	3732	3733	0.03
K-400 +20% Fly Ash	3667	3670	0.08
	3734	3736	0.05
K-400 + 30% Fly Ash	3733	3737	0.11
	3741	3745	0.11
K-400 + 40% Fly Ash	3638	3641	0.08
	3786	3787	0.03

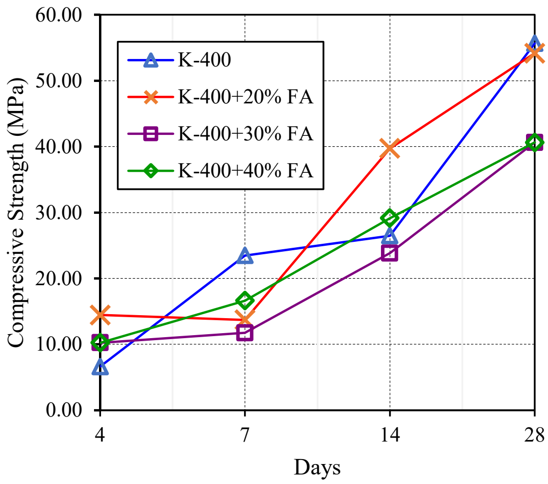

Fig. 2 Compressive strength for each cylindrical concrete specimen

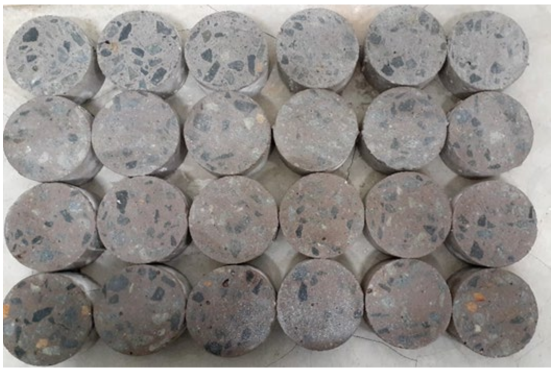

Fig. 3 Concrete discs

Therefore, 16 concrete discs were used for the migration test under steady-state conditions. As illustrated in Table 1, the concrete discs were labelled based on the quantity of fly ash material, the load, and the testing period (Table 3).

For the steady-state migration test, concrete discs from Table 3 were utilized. The test utilizes concrete 1-8 for seven days (168 hours). Every 12 hours, 10 ml samples were taken from the second compartment to determine the chloride concentration. Additionally, the test employs concrete #9-16 for fourteen days (336 hours). Every 24 hours, 10 ml samples of the second compartment were collected to determine the chloride concentration. The concentration of chloride was then analysed to determine the effect of load and fly ash materials in the concrete mixture.

Fig. 4 Sample of a pre-loaded concrete specimen, showing specimen #5

Figs. 5-8 illustrate the chloride concentration trends in the second compartment for both loaded and non-loaded concrete specimens over 7-day and 14-day testing periods. In the 7-day tests (Figs. 5 and 6), it is evident that loaded concrete specimens consistently exhibit higher chloride concentrations than their non-loaded counterparts, regardless of fly ash content. This indicates that the applied load alters the microstructure of concrete, possibly by inducing microcracks or reducing the interlocking between cement paste and aggregate, which facilitates greater chloride ion penetration. Nevertheless, the incorporation of fly ash into the concrete mix effectively reduces chloride concentration in both conditions. For instance, by the end of the 7 days, chloride concentration in non-loaded specimens containing fly ash decreased by 61.3% compared to specimens without fly ash, while loaded specimens achieved a greater reduction of 79.8%.

In the 14-day testing period (Figs. 7 and 8), the influence of both fly ash and loading becomes more pronounced. Chloride concentration decreased progressively with increasing fly ash content, indicating and reaffirming the pozzolanic and pore-refining benefits of fly ash. Non-loaded specimens containing 20%, 30%, and 40% fly ash show reductions in chloride concentration of 63.60%, 68.62%, and 75.57%, respectively, compared to concrete without fly ash. Similarly, for loaded specimens, the reductions are 52.61%, 57.84%, and 69.40%.

In the 7-day and 14-day tests (Figs. 6 and 8), pre-loaded specimens consistently showed higher chloride concentrations than non-loaded ones. This is attributed to microcracking caused by the 2,000 kg load, which likely altered the pore structure and enhanced chloride transport. Prior to selecting the 2,000 kg load for pre-damaging, preliminary compression tests (data not shown) on concrete discs with and without fly ash showed failure loads ranging from 2,300 to 3,800 kg, depending on fly ash content and curing. A 2,000 kg load was chosen to stay below the failure limit, allowing microcrack formation without structural failure. This simulates service-level stress that may promote chloride ingress. Although visual cracking was observed after loading, crack widths were not measured in this study. Furthermore, previous studies support that chloride ingress increases significantly at stress levels above 50–75% of the ultimate compressive strength due to microcrack formation [10]. The elevated chloride concentration in the loaded specimens aligns with this well-established behavior, and the loaded condition can be considered as representing a pre-damaged state with increased permeability under service loads.

Table 3. Concrete discs for the steady-state migration test

Pre-load (kg)	Testing Period (Days)	Concrete#	Fly Ash Content	Case Code
0	7	1	0%	NL-7-0
		2	20%	NL-7-20
		3	30%	NL-7-30
		4	40%	NL-7-40
2,000	7	5	0%	L-7-0
		6	20%	L-7-20
		7	30%	L-7-30
		8	40%	L-7-40
0	14	9	0%	NL-14-0
		10	20%	NL-14-20
		11	30%	NL-14-30
		12	40%	NL-14-40
2,000	14	13	0%	L-14-0
		14	20%	L-14-20
		15	30%	L-14-30
		16	40%	L-14-40

These results emphasize that while loading increases chloride penetration, higher fly ash content mitigates this effect and enhances the concrete's durability. The gap in chloride concentration between loaded and non-loaded specimens narrows as fly ash content increases, suggesting that fly ash not only improves chemical resistance but may also contribute to structural resilience under load.

Because of its smaller particle size, fly ash can offer greater resistance to chloride than cement, coarse, and fine aggregate particles. The smaller particle size fills the voids in the concrete microstructure, thereby enhancing its resistance to chloride. The observed pore-refining effect of fly ash, inferred from the reduced chloride concentrations, aligns with recent microstructural analyses that demonstrate how fly ash particles and their secondary hydration products fill capillary voids and densify the matrix [15]. Our finding that higher replacement levels (up to 40%) yield progressively greater resistance is consistent with long-term exposure studies. However, some research suggests that an optimal replacement level may exist around 30%, depending on the specific materials and curing conditions [13].

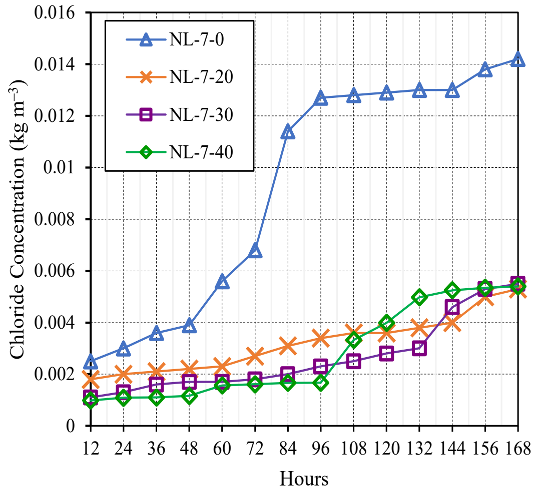

Fig. 5 Chloride concentration in the second compartment over a 7-day testing period for non-loaded concrete specimens with varying fly ash content

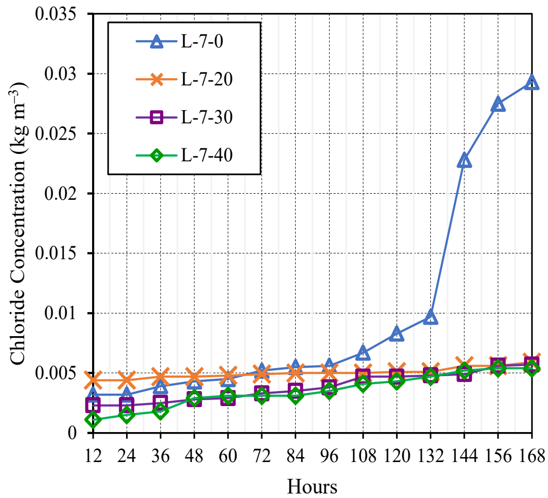

Fig. 6 Chloride concentration in the second compartment over a 7-day testing period for loaded concrete specimens with varying fly ash content

As shown in Fig. 9, the chloride concentration after 14 days of testing is relatively higher than after 7 days. After the 7-day testing period, only concretes 5 and 13 (loaded K-400 concrete) exhibit a higher chloride concentration than those tested for 14 days. However, due to the slight difference between them, the results still suggest that a more extended testing period will result in a higher chloride concentration.

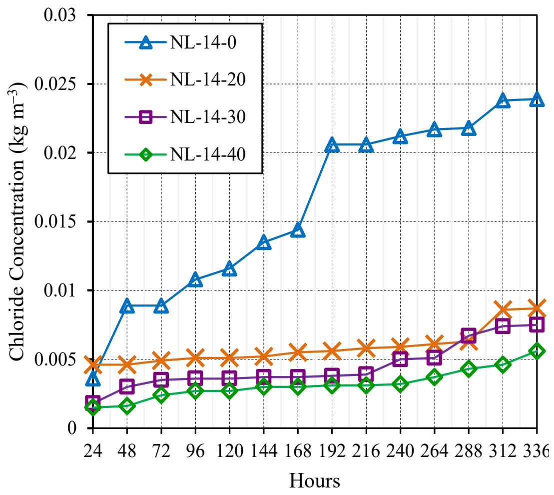

Fig. 7 Chloride concentration in the second compartment over a 14-day testing period for non-loaded concrete specimens with varying fly ash content

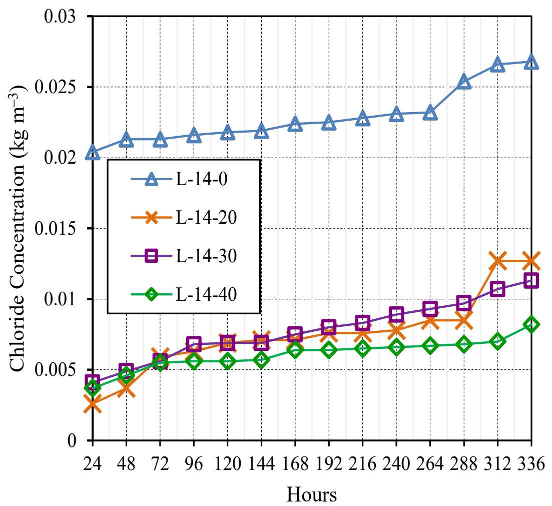

Fig. 8 Chloride concentration in the second compartment over a 14-day testing period for loaded concrete specimens with varying fly ash content

Comparisons of chloride diffusion rates across specimens are described in Fig. 10. The blue bar illustrates the rate of chloride diffusion for concrete 1-8 after 7 days of testing, while the orange bar represents the rate of chloride diffusion for concrete 9-16 after 14 days of testing.

Using Eqs. (2) and (3), the chloride diffusion rate was calculated as shown in Fig. 10. To improve accuracy and account for slight thermal variations between specimens, the average test temperature of each specimen (Table 4) was used in the Nernst–Planck calculation. This ensures that any temperature-dependent effects on ion mobility are appropriately considered. Although the temperature fluctuations were minimal, ranging from 298.0 K to 298.95 K, this approach ensures that any potential thermal effects on ion mobility are accounted for and normalized within the results.

Table 4. Voltage drop and temperature

Concrete#	Voltage Drop (mV)	Temperature (K)	Case Code
1	17	298.1	NL-7-0
2	14	298.2	NL-7-20
3	28	298.2	NL-7-30
4	20	298	NL-7-40
5	34	298.1	L-7-0
6	18	298.8	L-7-20
7	11	298.6	L-7-30
8	9	298.5	L-7-40
9	11	298.85	NL-14-0
10	10	298.75	NL-14-20
11	12	298.85	NL-14-30
12	12	298.95	NL-14-40
13	8	298.35	L-14-0
14	12	298.25	L-14-20
15	11	298.25	L-14-30
16	8	298.25	L-14-40

Applying load was found to accelerate chloride ingress, aligning with Djerbi et al., who showed that diffusion increases with crack width. However, our results reveal that adding fly ash can mitigate this effect, reducing chloride concentration by 79.8% in loaded specimens, underscoring its key role in improving durability under load [2].

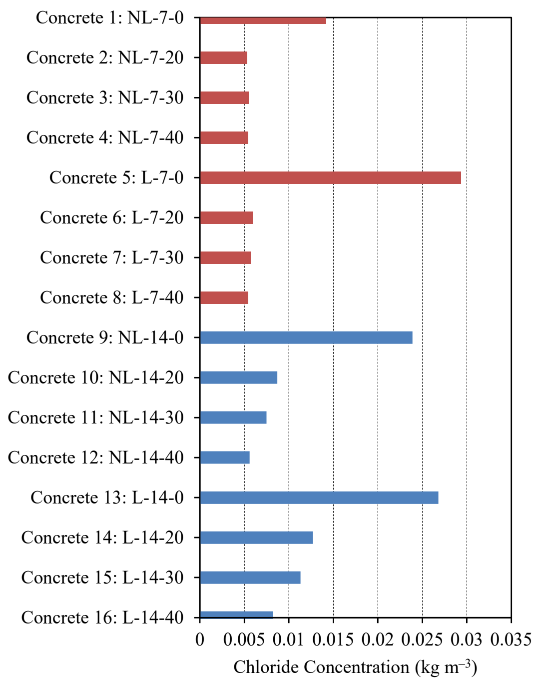

Fig. 9 Chloride concentration observed after the testing

As indicated in Fig. 10, the rate of chloride diffusion is higher in concretes 1 and 5, which do not contain fly ash additions. The analysis of chloride concentration suggests that specimens of concrete without fly ash will have a higher chloride concentration value, leading to increased chloride ion flux (J) and chloride diffusion rate. Concrete 5, being a loaded concrete, provides a higher chloride diffusion rate than Concrete 1.

Although the addition of fly ash enhances chloride resistance, the chloride diffusion rate is not solely determined by chloride concentration. As observed in concretes 6, 7, and 8, the concrete with the lowest voltage drop demonstrates the highest chloride diffusion rate. This trend is also evident in concretes 2, 3, and 4, with concrete 2 showing the highest chloride diffusion rate due to its low voltage drop value. Alongside chloride concentration, the voltage drops across specimens are also a significant factor in determining the chloride diffusion rate.

As shown in Table 4, the voltage drop and temperature across the specimens are measured to determine the chloride diffusion rate.

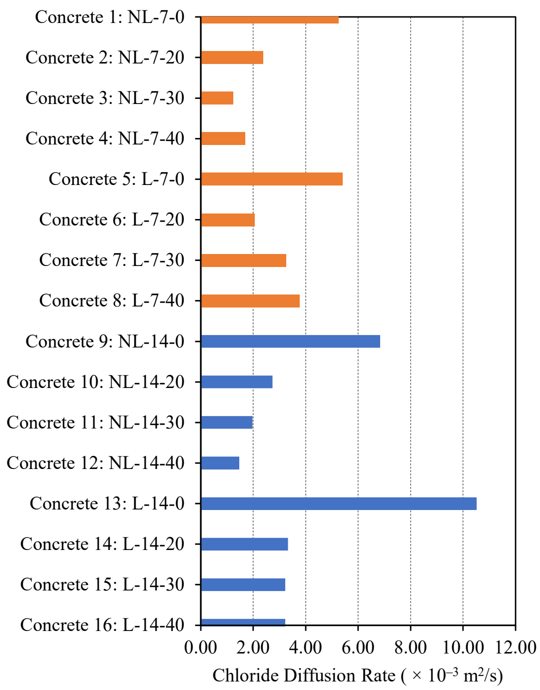

Fig. 10 Chloride diffusion rate across specimens

During the 14-day testing period, superior performance is observed in chloride diffusion rates. As seen in concrete 10-12, chloride diffusion rates decrease as fly ash content increases, attributed to the decrease in chloride concentration and voltage drop. While chloride concentration is the primary observable outcome of ion migration, the calculated diffusion coefficient (D_e) is also inversely dependent on the voltage drop across the specimen. According to Eq. (2), a small voltage drop (E) increases the computed D_e, even if chloride flux is modest. This nonlinear relationship explains why some specimens with low chloride concentrations still exhibited relatively high D_e values, particularly in the 14-day loaded series (Concretes 14-16). This highlights the need for careful interpretation of D_e values when voltage drops vary significantly across specimens, and future studies should consider normalizing or stabilizing E during testing to reduce this source of variation.

Moreover, since only one specimen per condition was tested, inherent material variability or localized microcracks under loading may have influenced the chloride transport behavior. Future studies should incorporate multiple specimens and detailed microstructural analysis to confirm these findings. In general, chloride diffusion rates for 14 days of testing exceed those for 7 days of testing. However, concretes containing 40% fly ash exhibit lower chloride diffusion rates compared to those measured after 7 days.

5. CONCLUSION

This study evaluated the influence of fly ash replacement and pre-applied mechanical loading on chloride diffusion in high-strength concrete using the NT Build 355 steady-state migration test. The results demonstrated that increasing fly ash content consistently reduced chloride ingress, even under mechanical loading conditions. The greatest reduction, up to 79.8%, was observed in specimens with 40% fly ash replacement under load. These results highlight the important role of fly ash in improving the durability performance of concrete exposed to chloride environments.

Fly ash addition also contributes to sustainability by reducing cement usage and its associated carbon dioxide emissions. Based on the findings, a 30–40% replacement of cement with fly ash is recommended to enhance chloride resistance and reduce cement-related carbon emissions in reinforced concrete structures exposed to marine environments. The diffusion coefficients obtained in this study can support service-life prediction and durability-based design.

Future research should examine the sustained load during migration tests, including the effects of cyclic or fatigue loading, sensitivity to voltage and chloride flux environmental fluctuations, define the critical load level, perform statistical analysis for each case, and conduct long-term field exposure to validate and expand on these findings.

6. ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation to the Research, Community Service, and Innovation (PPMI) Program of Institut Teknologi Bandung for the financial support provided to complete this research. The funding played a vital role in facilitating the experimental

work, data analysis, and overall progress of the study.

7. REFERENCES

1. Adiyastuti S.M., Iqbal B., and Ilman E.C., Effect of cracking in fly ash concrete on chloride diffusion rate. IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2025, pp. 1-9. https://doi.org/10.1088/1755-1315/1464/1/012030
2. Djerbi A., Bonnet S., Khelidj A., and Baroghel-Bouny V., Influence of traversing crack on chloride diffusion into concrete. Cement and Concrete Research, Vol.38, No.6, 2008, pp. 877-883. https://doi.org/10.1016/j.cemconres.2007.10.007
3. Aldea C.M., Shah S.P., and Karr A., Effect of cracking on water and chloride permeability of concrete. Journal of Materials in Civil Engineering, Vol.11, No.3, 1999, pp. 181-187. https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(181)
4. Sugiyama T., Bremner T., and Tsuji Y., Determination of chloride diffusion coefficient and gas permeability of concrete and their relationship. Cement and Concrete Research, Vol.26, No.5, 1996, pp.7 81-790. https://doi.org/10.1016/S0008-8846(96)85015-0
5. Heirman G., Vandewalle L., and Kovler K., Chloride penetration and carbonation in self-compacting concrete. Proc. of the International RILEM/JCI Seminar on Concrete Durability and Service Life Planning, RILEM Publications SARL, Bagneux, 2006, pp. 13-23.
6. Nordtest Method, NT Build 355. Nordtest, 1999, pp.1–4.
7. Kosior ‐ Kazberuk M. and Lelusz M., Strength development of concrete with fly ash addition. Journal of Civil Engineering and Management, Vol.13, No.2, 2007, pp. 115-122. https://doi.org/10.3846/13923730.2007.9636427
8. Elsageer M.A., Millard S.G., and Barnett S.J., Strength development of concrete containing coal fly ash under different curing temperature conditions. World of Coal Ash (WOCA) Conference, 2009, pp. 1–11.
9. Wang X.-Y. and Park K.-B., Analysis of compressive strength development of concrete containing high volume fly ash. Construction and Building Materials, Vol.98, 2015, pp. 810–819. https://doi.org/10.1016/j.conbuildmat.2015.08.099
10. Liu X., Li H., Qi M., Yang Y., Zhu Z., and Yu Z., Experimental study on the influence of transverse crack on chloride ingress in concrete slab track of high-speed railway. Materials, Vol.16, No.9, 2023, pp. 1-17. https://doi.org/10.3390/ma16093524
11. Pane I., Imran I., and Budiono B., Compressive strength of fly ash-based geopolymer concrete with a variable of sodium hydroxide (NaOH) solution molarity. MATEC Web of Conferences, EDP Sciences, 2018, pp. 1-5. https://doi.org/10.1051/matecconf/201814701004
12. Adiyastuti S.M., Influence of cracks on chloride induced corrosion in reinforced concrete flexural members. Master's Thesis, 2005, pp. 1–187. https://doi.org/10.26190/unsworks/17661
13. Zhang J., Zhou X.Z., Zheng J.J., Ye H.L., and Yang J., Experimental investigation and analytical modeling of chloride diffusivity of fly ash concrete. Materials, Vol.13, No.4, 2020, pp. 1-12. https://doi.org/10.3390/ma13040862
14. Cuong N.H., Study on compressive strength and chloride ion permeability of high fly ash content self-compacting concrete. International Journal of GEOMATE, Vol.26, No.113, 2024, pp.34–40. https://doi.org/10.21660/2024.113.4164
15. Liu J., Liu J., Huang Z., Zhu J., Liu W., and Zhang W., Effect of fly ash as cement replacement on chloride diffusion, chloride binding capacity, and micro-properties of concrete in a water soaking environment. Applied Sciences, Vol.10, No.18, 2020, pp. 1-16. https://doi.org/10.3390/app10186271
16. Ma Y., Zhang J., Yang X., Yang Z., Zhang Z., and Wang H., Assessing the long-term chloride resistance of alkali-activated fly ash/slag concrete by natural chloride diffusion test and rapid chloride migration test. Construction and Building Materials, Vol.472, 2025, pp. 1-23. https://doi.org/10.1016/j.conbuildmat.2025.140823