Chloride Penetration in Low-Carbon Concrete with High Volume of SCM: A Review Study

C. Xue and V. Sirivivatnanon

Abstract Low-carbon concrete (LCC) uses supplementary cementitious material (SCM) to partially replace cement as a method for reducing its carbon footprint. Previous laboratory and field studies had provided substantial support and experience for using LCC in marine structures, which are the most susceptible to chloride-induced corrosion. Some short-term test methods have provided reliable assessment of the ability of LCC to resist chloride penetration, but the long-term chloride penetration depends on a great many factors and thus could differ from the results obtained from laboratory tests. However, the lack of a correlation between the data from short-term and long-term tests has limited the use of abundant laboratory results for service life design of LCC. This study presents an overview of results obtained when LCCs were exposed to chlorides. The key outcome of this study is a broader synthesis of the available data regarding the relationship between the mix design and the performance of LCCs in various chloride environments, which helps find the possible correlation and fully appreciate the value of the short-term tests.

Keywords Chloride penetration · Low carbon concrete · Marine structures

1 Introduction

Approximately 5–8% of the global CO_2 emissions is attributed to the production of ordinary Portland cement (OPC) [1]. To reduce the carbon footprint of the concrete industry, substitution of cement by supplementary cementitious materials (SCM) without compromising performance is an efficient solution [2]. Another indirect way to contribute to sustainability is prolonging the service life of infrastructure by using durable concrete. From these two viewpoints, ground granulated blast-furnace

---

C. Xue (✉) · V. Sirivivatnanon
School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW, Australia
e-mail: Caihong.Xue@uts.edu.au

UTS-Boral Center for Sustainable Building, Sydney, NSW, Australia

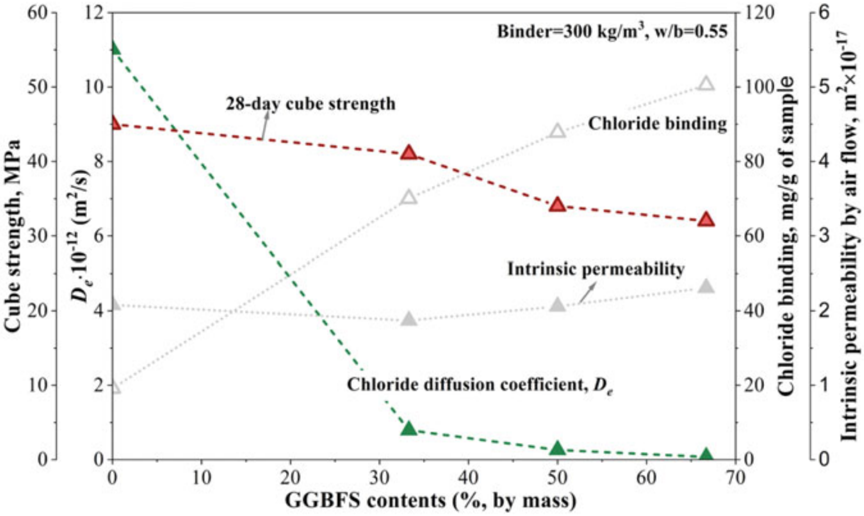
W. Duan et al. (eds.), *Nanotechnology in Construction for Circular Economy*, Lecture Notes in Civil Engineering 356,
https://doi.org/10.1007/978-981-99-3330-3_16

slag (GGBFS) and fly ash (FA) are great choices among other SCMs. One of the major benefits of blending OPC with GGBFS or FA is improved resistance to chloride penetration, which has been evidenced by both short-term laboratory tests and long-term field tests. The former includes the widely used rapid chloride migration test method standardized in ASTM C1202 [3] and the chloride diffusion test given in NT Build 492 [4]. However, for application, concrete structures need to be designed for a specific service life, and this requires long-term quantitative field performance assessment, which is not always practical [5]. Therefore, finding the link between the results from laboratory and field tests is important for promoting efficient use of LCCs, but is nevertheless challenging because a high concentration of deleterious species in laboratory tests could have already altered the deterioration processes and the laboratory curing conditions deviate significantly from on-site conditions. The purpose of this paper was to review of the factors affecting chloride penetration in LCC made with GGBFS or FA and the correlations between results from different test methods.

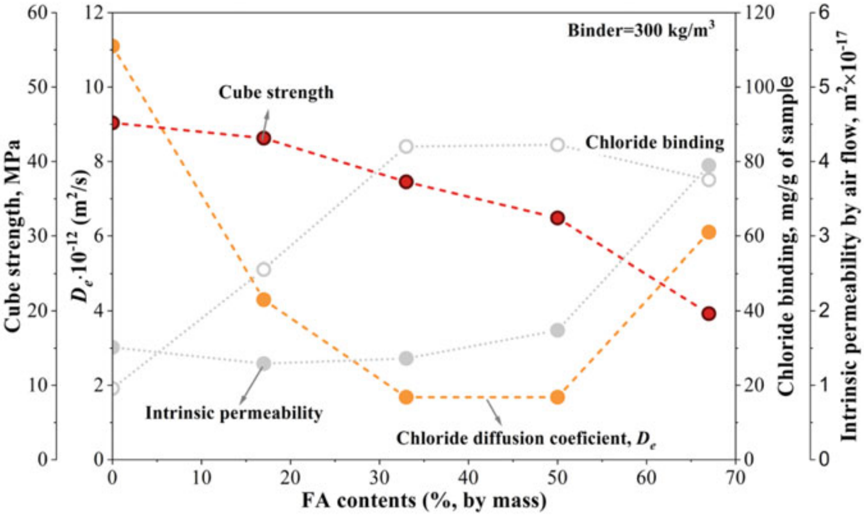
2 Chloride Penetration in LCC

2.1 Effect of SCM Content on Diffusion Coefficients

The replacement of cement with SCM is usually no more than 50% for GGBFS and 30% for FA, due to the reduction in strength with increasing SCM content, as shown in Fig. 1, in which the short-term laboratory test results from Dhir et al. [6] were adopted to demonstrate the effect of GGBFS or FA content on D as well as the 28 day cube strength. It can be seen that the diffusion coefficients continuously decrease with increasing GGBFS content up to 65%; in the range of 30–50%, D is insignificantly affected by FA content but the strength reduction is more pronounced at higher FA dosages. On the other hand, for high-volume FA (HVFA) concrete with >50% FA as cement replacement and a considerably high amount of superplasticizer, the HVFA concrete has proven to yield higher long-term strength and resistance against chloride penetration than OPC concrete, despite the early-age properties of the former being less competitive [7–10]. Thomas et al. [11, 12] found that HVFA concrete with 50% FA had a significantly lower D and a slightly higher compressive strength than OPC concrete after being exposed to the field marine environment for up to 10 years. Moreover, Moffatt et al. [13] reported the D of a HVFA concrete with 56–58% FA after 24 years of exposure to a harsh field environment where high tides and freeze–thaw cycles occurred, was only 1.5×10^{-13} m^2/s compared with 3.6×10^{-12} m^2/s for the counterpart OPC concrete.



(a) GGBFS content



(b) FA content

Fig. 1 Effects of **a** ground granulated blast-furnace slag (GGBFS) and **b** fly ash (FA) content as cement replacement on chloride penetration and other properties assessed by short-term laboratory tests [6, 14, 15]

2.2 Effect of Curing Conditions on Chloride Penetration

It has been well established that partial replacement of cement by GGBFS or FA improves the microstructure of concrete and thus the resistance to chloride penetration. In LCC, the GGBFS or FA reacts with calcium hydroxide (formed by the hydration of cement) and water to produce C–S–H and a portion of calcium aluminate phases [16–18]. Additionally, depending on the specific surface area of particles, GGBFS or FA can act as a filler to fill pores and as nucleation sites to enhance hydration [19, 20]. Apart from the products formed by normal cement hydration, the additional hydrates due to either enhanced hydration or hydration of GGBFS/FA reduce capillary porosity (>30 nm) and thus block the chloride diffusion paths; however, these benefits of GGBFS and FA depend on the curing conditions, especially for LCC with GGBFS [21]. Moreover, it is possible that blended cement concrete will perform no better than OPC concrete when structures are exposed to prolonged drying and carbonation [22]. Figure 2 compares the D of concretes cured in wet and dry conditions, from which it can be seen that OPC concrete with a low strength grade is more sensitive to the curing conditions, and the influence of curing conditions diminishes with increasing concrete strength and exposure duration [23, 24]. Irrespective of the curing conditions, at the same grade the blended concretes consistently outperform OPC concrete in resisting chloride penetration. In this regard, Bamforth [25] examined the D of dry-cured (indoor), membrane-cured and water-cured concrete blocks (40 MPa at 28 days) located in the splash/spray zone on the south coast of the UK for 8 years, and found that the effect of curing conditions on the D of different concrete mixes was inconsistent, but that 70% GGBFS-blended concrete yielded the lowest average D compared with 30% FA-blended concrete and OPC concrete. Additionally, a lower grade of blended cement concrete is more durable than a higher grade OPC concrete at the later age, which was also confirmed by Thomas et al. [11].

2.3 Effect of Test Methods on Chloride Penetration

There are only limited published data on relating laboratory test results to long-term field performance of concrete with regard to resistance to chloride penetration. Figure 3 shows the correlation between D from a long-term field test (D_{field} on the x-axis) and counterpart D from laboratory diffusion tests (D_{lab} on the left y-axis) and coulombs (right y-axis) from the rapid chloride permeability test (RCPT), using data from previous studies [13, 26, 27]. Thomas et al. [26] conducted the RCPT as well as diffusion tests (using 16.5% NaCl as per ASTM C1556) on uncontaminated GGBFS-blended concrete exposed in the field to a tidal zone for 25 years, and calculated the chloride diffusion coefficient (D_{field}) from the chloride profiles in the field-exposed concrete. Moffatt et al. [13] obtained D_{field} and coulombs (RCPT) of high-volume FA concrete exposed to the marine environment for 19–24 years. Compared with the results from the RCPT, D_{lab} from laboratory diffusion tests following the procedures

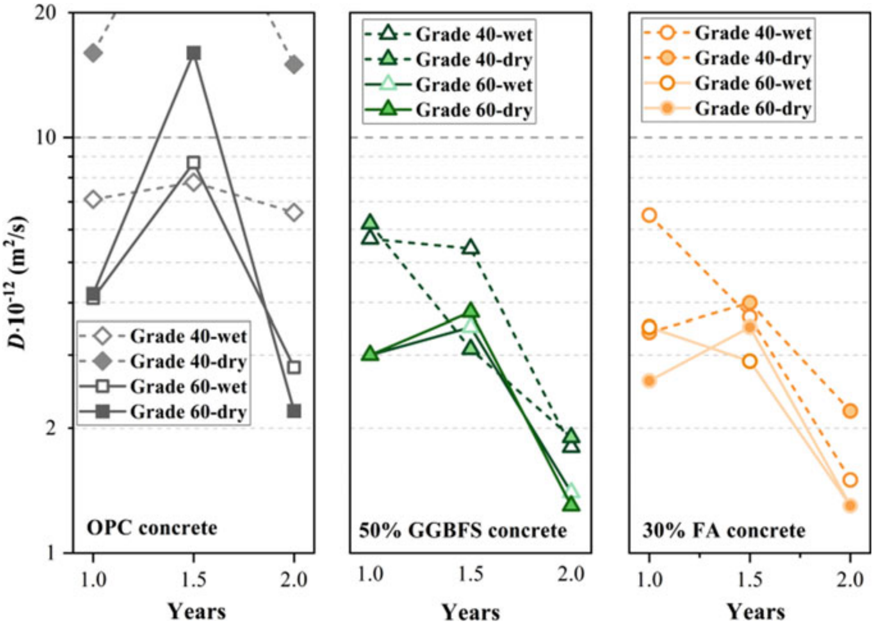


Fig. 2 Effect of curing conditions on the *D* of different grades of concrete exposed to the tidal zone of Cape Peninsula with water temperature between 12 and 15 °C. The wet-cured (wet) concrete was exposed to 6 days' moist curing (23 °C and 90% relative humidity) after demolding, while the dry-cured (dry) concrete was stored in an open area (23 °C and 50% relative humidity). The concrete was exposed to marine environment at age 28 days [23]. GGBFS, ground granulated blast-furnace slag; FA, fly ash; OPC, ordinary Portland cement

given in ASTM C1556, NT Build 443 or other similar procedures, could better indicate the ability of concrete to resist chloride penetration. Although there are synergies between the two diffusion coefficients (D_{lab} and D_{field}), the quantitative relationship between them varies. Figure 4 shows the correlation between D_{lab} (x-axis) and coulombs from the RCPT (left y-axis), and the non-steady-state (D_{nssm}) or steady-state (D_{ssm}) chloride migration coefficient (D_m on the right y-axis) from accelerated migration tests reported in previous studies [28–32]. Note that these previous studies used different NaCl concentrations and exposure durations, which are summarized in Table 1. When D_{lab} was used as the reference, the $D_m > 2 \times 10^{-12}$ (m^2/s) and RCPT coulombs >800 could be more reliable for ranking concretes in terms of the resistance to chloride penetration.

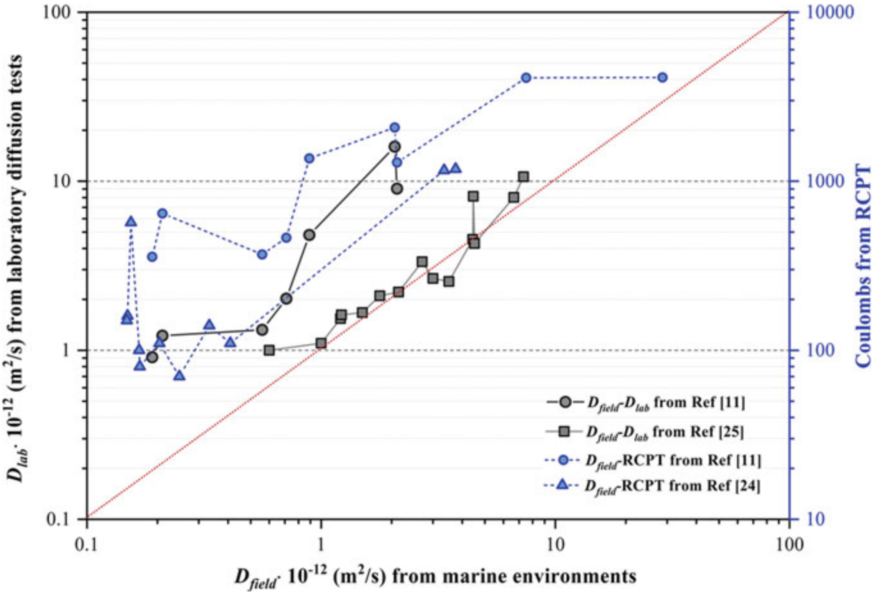


Fig. 3 Correlation between the D from marine exposure (D_{field}) and the D from laboratory diffusion tests (D_{lab}) and coulombs from the rapid chloride permeability test (RCPT) [13, 26, 27]

3 Conclusions

(1) Replacing cement with up to 65% GGBFS or 30% FA improves the resistance of concrete to chloride penetration but decreases early-age strength development. LCC with GGBFS or FA could achieve higher resistance to chloride penetration at equivalent strength or binder content as compared with OPC concrete, indicating that efficient use of LCC requires a performance-based service life design approach.

(2) The influence of curing conditions on chloride diffusion coefficients diminishes with increasing concrete strength grade, but could be significant for low-strength concrete. At strength grade $\geq$40 MPa, the difference in chloride diffusion coefficients arising from the change in curing conditions is much smaller in LCC than OPC.

(3) Although short-term laboratory diffusion and accelerated migration tests are reliable in distinguishing parameters that affect chloride penetration in concrete, the correlations between results from different methods are difficult to establish.

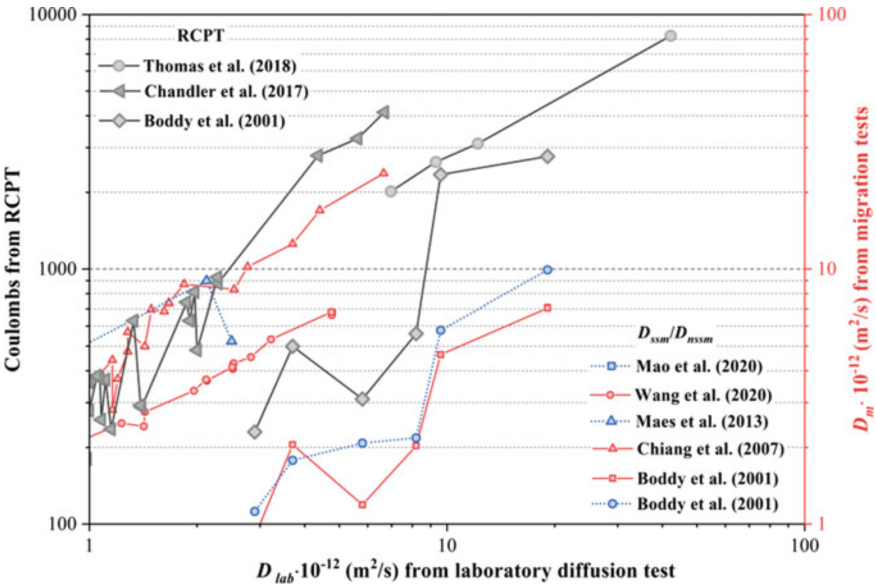


Fig. 4 Correlation between the D from laboratory diffusion tests (D_{lab}) and coulombs from the rapid chloride permeability test (RCPT) and the chloride migration coefficient from migration tests (D_m) [28–32]. The gray lines indicate the RCPT results. The red lines indicate the steady-state chloride migration coefficient (D_{ssm}) and blue lines indicate non-steady-state chloride migration coefficient (D_{nssm})

Table 1 Laboratory test methods for assessing resistance to chloride penetration shown in Fig. 4

Authors	Laboratory diffusion tests			Accelerated migration tests		
	Standard	NaCl	Days	Standard	NaCl	Hours/voltage
Thomas et al. [28]	ASTM C1543	3%	90			
Maes et al. [29]	NT Build 443	16.5%	30	NT Build 492	10%	24/30–60
Boddy et al. [30]	AASHTO T259	3%	90			
Chiang and Yang [31]	AASHTO T259	3%	90	ACMT	0.52 M	24/60
Mao et al. [32]	NT Build 443	16.5%	90	NT Build 492	10%	24/60
Wang and Lui [33]		0.1 M	42–49		0.1 M	24–48/12

Acknowledgements The authors acknowledge the support of the UTS-Boral Centre for Sustainable Building for the opportunity to review the performance-based testing of the resistance of LCC to chloride penetration. This will promote greater and systematic use of LCC in marine environments.

References

1. Habert G, Billard C, Rossi P, Chen C, Roussel N (2010) Cement production technology improvement compared to factor 4 objectives. Cem Concr Res 40(5):820–826
2. Bilodeau A, Malhotra VM (2000) High-volume fly ash system: concrete solution for sustainable development. Mater J 97(1):41–48
3. ASTM-C1202-12 (2012) Standard test method for electrical indication of concrete stability to resist chloride ion penetration. ASTM Annual Book of Standards, V.04.02, ASTM International, 100 Barr Harbour Dr., P.O. box C-700, West Conshohocken, PA USA
4. NT BUILD 492 (1999) Concrete, mortar and cement-based repair materials: chloride migration coefficient from non-steady-state migration experiments, Nordtest method
5. Beushausen H, Torrent R, Alexander MG (2019) Performance-based approaches for concrete durability: state of the art and future research needs. Cem Concr Res 119:11–20
6. Dhir R, El-Mohr M, Dyer T (1996) Chloride binding in GGBS concrete. Cem Concr Res 26(12):1767–1773
7. Giaccio GM, Malhotra V (1988) Concrete incorporating high volumes of ASTM Class F fly ash. Cem, Concr Aggreg 10(2):88–95
8. Dunstan M, Thomas M, Cripwell J, Harrison D (1992) Investigation into the long-term in-situ performance of high fly ash content concrete used for structural applications, vol 132. Special Publication, pp 1–20
9. Mehta PK (2004) High-performance, high-volume fly ash concrete for sustainable development. In: Proceedings of the international workshop on sustainable development and concrete technology. Iowa State University Ames, IA, USA, pp 3–14
10. Zuquan J, Wei S, Yunsheng Z, Jinyang J, Jianzhong L (2007) Interaction between sulfate and chloride solution attack of concretes with and without fly ash. Cem Concr Res 37(8):1223–1232
11. Thomas M (1991) Marine performance of PFA concrete. Mag Concr Res 43(156):171–185
12. Thomas M, Matthews J (2004) Performance of pfa concrete in a marine environment—10-year results. Cem Concr Compos 26(1):5–20
13. Moffatt EG, Thomas MD, Fahim A (2017) Performance of high-volume fly ash concrete in marine environment. Cem Concr Res 102:127–135
14. Dhir R, Hewlett P, Chan Y (1989) Near surface characteristics of concrete: intrinsic permeability. Mag Concr Res 41(147):87–97
15. Dhir R, El-Mohr M, Dyer T (1997) Developing chloride resisting concrete using PFA. Cem Concr Res 27(11):1633–1639
16. Kolani B, Buffo-Lacarrière L, Sellier A, Escadeillas G, Boutillon L, Linger L (2012) Hydration of slag-blended cements. Cem Concr Compos 34(9):1009–1018
17. Sakai E, Miyahara S, Ohsawa S, Lee S-H, Daimon M (2005) Hydration of fly ash cement. Cem Concr Res 35(6):1135–1140
18. Lam L, Wong Y, Poon CS (2000) Degree of hydration and gel/space ratio of high-volume fly ash/cement systems. Cem Concr Res 30(5):747–756
19. Gutteridge WA, Dalziel JA (1990) Filler cement: the effect of the secondary component on the hydration of Portland cement: part 2: fine hydraulic binders. Cem Concr Res 20(6):853–861
20. Berodier E, Scrivener K (2014) Understanding the filler effect on the nucleation and growth of C–S–H. J Am Ceram Soc 97(12):3764–3773
21. Ngala V, Page C (1997) Effects of carbonation on pore structure and diffusional properties of hydrated cement pastes. Cem Concr Res 27(7):995–1007

22. Thomas M, Matthews J (1992) Carbonation of fly ash concrete. Mag Concr Res 44(160):217–228
23. Mackechnie J, Alexander M (1997) Exposure of concrete in different marine environments. J Mater Civ Eng 9(1):41–44
24. Khatib JM, Mangat P (2002) Influence of high-temperature and low-humidity curing on chloride penetration in blended cement concrete. Cem Concr Res 32(11):1743–1753
25. Bamforth P (1999) The derivation of input data for modelling chloride ingress from eight-year UK coastal exposure trials. Mag Concr Res 51(2):87–96
26. Thomas M, Bremner T (2012) Performance of lightweight aggregate concrete containing slag after 25 years in a harsh marine environment. Cem Concr Res 42(2):358–364
27. Sirivivatnanon V, Xue C, Khatri R (2022) Design service life of low carbon concrete in marine tidal conditions (submitted). ACI Mater J
28. Thomas R, Ariyachandra E, Lezama D, Peethamparan S (2018) Comparison of chloride permeability methods for alkali-activated concrete. Constr Build Mater 165:104–111
29. Maes M, Gruyaert E, De Belie N (2013) Resistance of concrete with blast-furnace slag against chlorides, investigated by comparing chloride profiles after migration and diffusion. Mater Struct 46(1):89–103
30. Boddy A, Hooton R, Gruber K (2001) Long-term testing of the chloride-penetration resistance of concrete containing high-reactivity metakaolin. Cem Concr Res 31(5):759–765
31. Chiang C, Yang C-C (2007) Relation between the diffusion characteristic of concrete from salt ponding test and accelerated chloride migration test. Mater Chem Phys 106(2–3):240–246
32. Mao X, Qu W, Zhu P, Xiao J (2020) Influence of recycled powder on chloride penetration resistance of green reactive powder concrete. Constr Build Mater 251:119049
33. Wang J, Liu E (2020) The relationship between steady-state chloride diffusion and migration coefficients in cementitious materials. Mag Concr Res 72(19):1016–1026