Achieving Sustainable Concrete through
use of Mineral Admixtures

Enhanced chloride resistance of concretes with mineral admixtures

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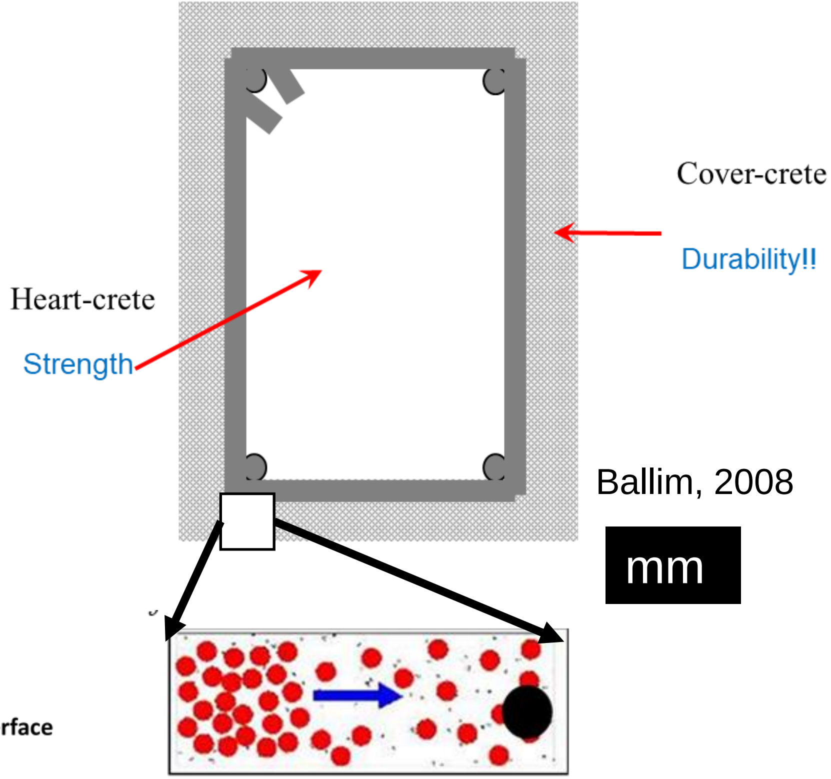
Introduction

- Background on chloride attack
- Role of chloride transport
- Chloride transport parameter
    - Time and temperature
    - Chloride binding
- Test methods to assess chloride resistance
- Role of mineral admixtures
    - Importance of chloride transport on chloride build-up rate at steel surface
    - Predicting chloride ingress
- Summary

Chloride transport in RC Structure -> Concrete cover -> Pores

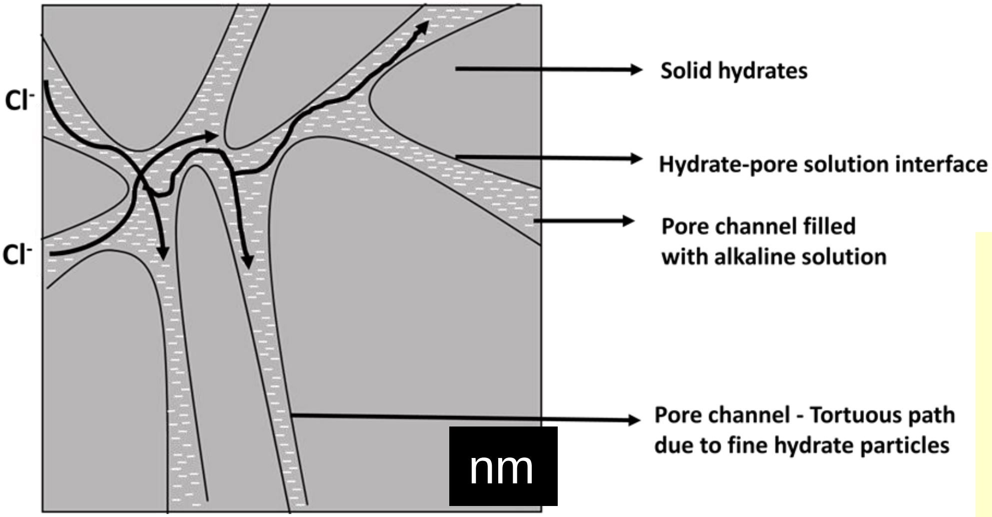
RC structure in marine environment (Corrosion!)

Concrete cover (governing medium)



Ballim, 2008

Pores in binding matrix (controlling factor)



Dhandapani et al. (in prep.)

Chloride transport in concrete systems involves several phenomenon at multiple scale
Chloride ingress - major source for corrosion related problem

Why chloride transport is important?

Transport of chlorides by diffusion governs service life in marine exposure

Crank's solution
Fick's 2nd law

$$C(x = X, t) = C_o + (C_{s, \Delta x} - C_o) \cdot \left[1 - \mathrm{erf}\left(\frac{X - \Delta x}{2\sqrt{D_{app, T,}\left(\frac{t_{ref}}{t}\right)^{m} \cdot t}}\right)\right]$$

C_s - surface chloride conc.

-Exposure conditions governs the build up rate of surface chloride conc.

C(x) - Conc. at steel surface

- When C(x)> C_{th} - corrosion initiates

C_o - initial chloride content in the concrete

X is the cover depth

D_{app} = Diffusivity of concrete in m^2/s

There is no one point solution for all these parameter as chloride ingress is specific to

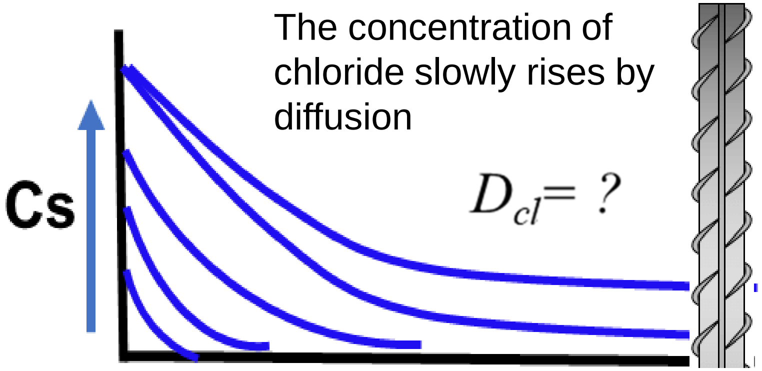
- location (Cs)
- particular concrete D_{cl}
- climate conditions D_{cl}(temp)
- ageing of concrete D_{cl}(time)

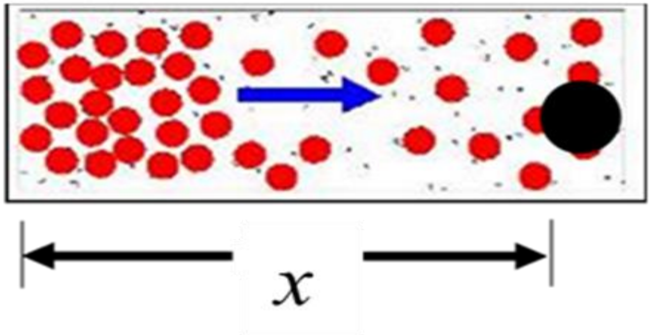
- All parameters are important to consider
- Target service life should be attained by controlling cover depth and chloride transport parameter

Chloride Transport Parameter (Dcl)

Chlorides diffuse through the concrete cover

Chloride transport parameter is controlled by concrete type, w/b and choice of SCMs





Diffusion rate

$$D(t) = Ke.Dapp.A(t)$$

Migration rate

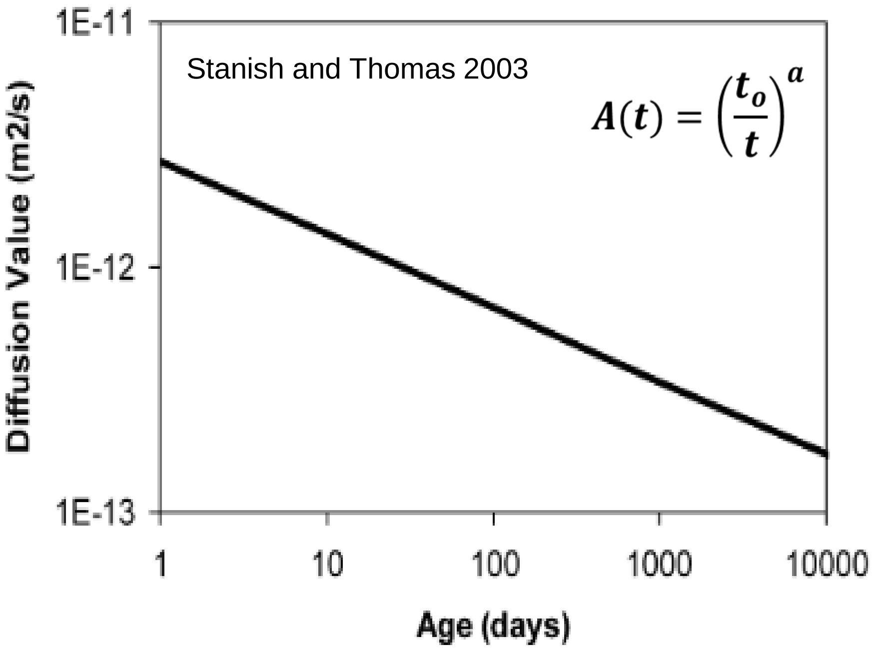
$$D(t) = Ke.DRCM.Kt.A(t)$$

Diffusion coefficient

- **Pore structure**
- **time**
- **temperature**
- **saturation level of concrete**
- **binding of chlorides**

$$D(t) = \mathrm{D_{app}}\left(\frac{t_{ref}}{t}\right)^m \qquad \mathrm{k_e} = \exp\left(\mathrm{b_e}\left(\frac{1}{\mathrm{T_{ref}}} - \frac{1}{\mathrm{T_{real}}}\right)\right)$$

D_{cl} varies as a function of time and temperature

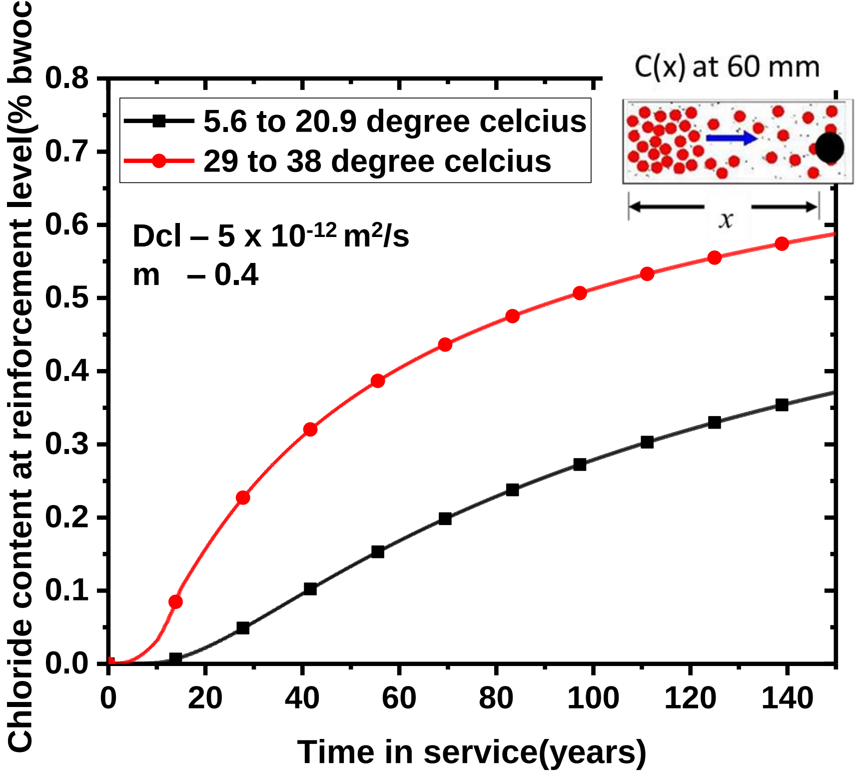


Decay coefficient from FIB 34

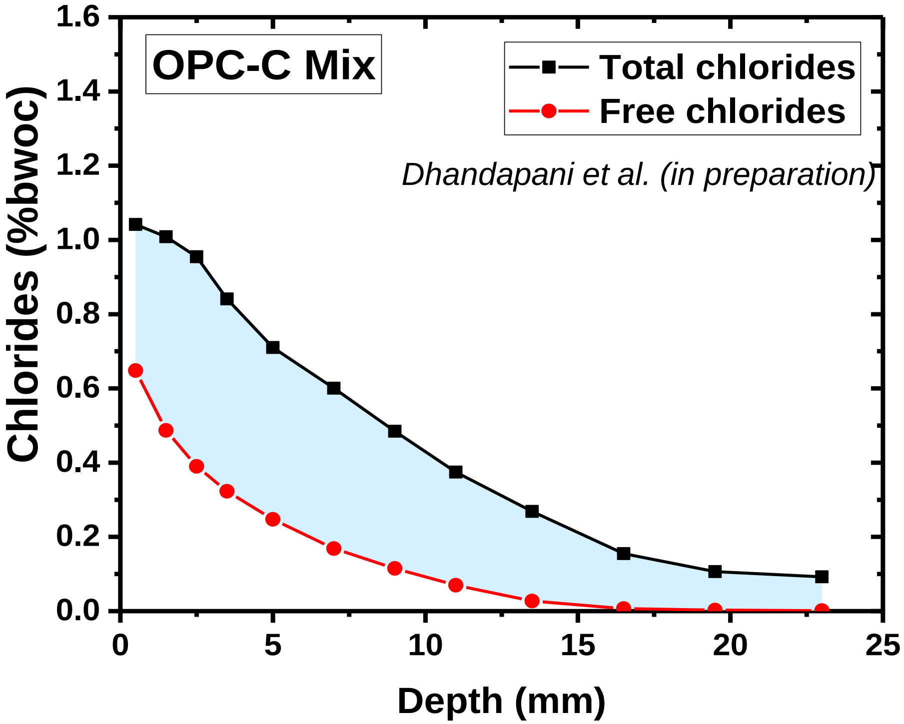
(Model Code for Service Life Design)

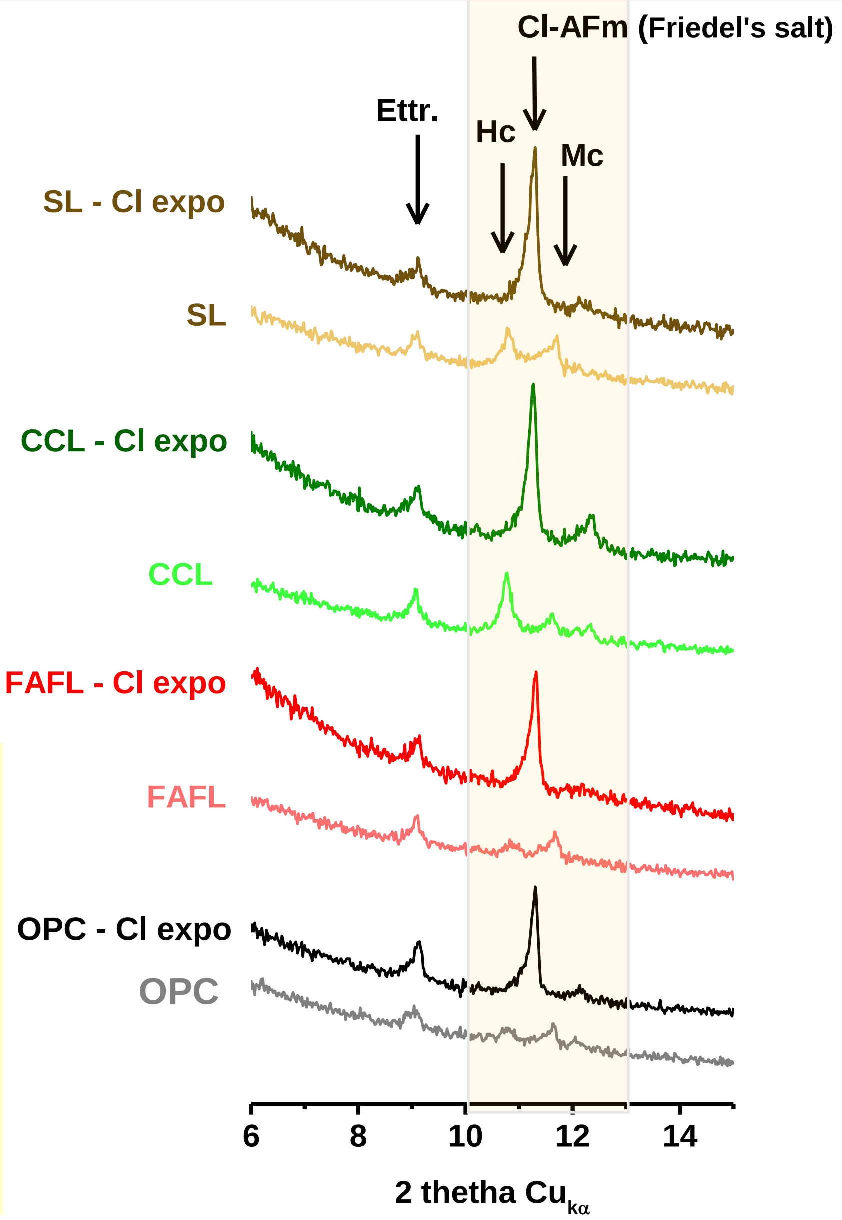
Binder type	Decay coefficient
OPC	0.3
Fly ash	0.6
Slag	0.45
Calcined clay	NA

- Diffusion coefficient reduces over time, especially with SCMs, which can be accounted using an factor ageing or decay coefficient
- In a practical scenario, chloride diffusion process is also a function of ambient (max-min) temperature condition



Chloride binding is beneficial with Al-rich SCMs

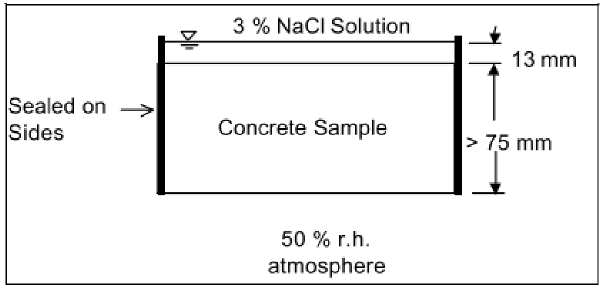




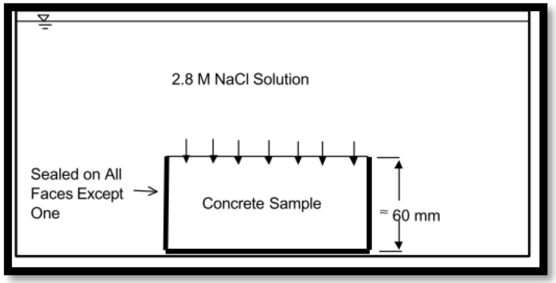
- Reduction in free chloride by chloride binding will lower the flux for diffusion

- All blended binders with Al rich SCMs such as Slag, fly ash and Calcined clay can facilitate chloride binding (Cl-AFm formation)

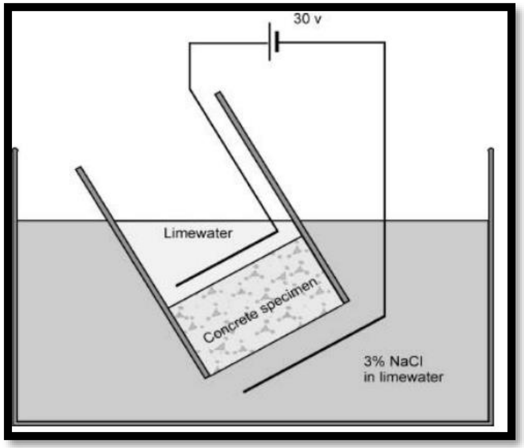
Performance tests for chloride penetrability



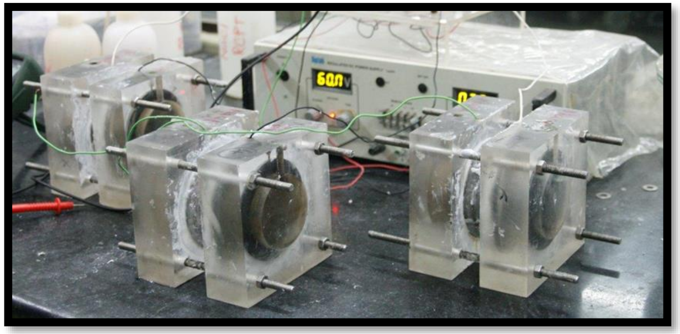
Ponding, AAHSTO T259 test



Bulk diffusion test
NTBuild 443/ASTM C1556

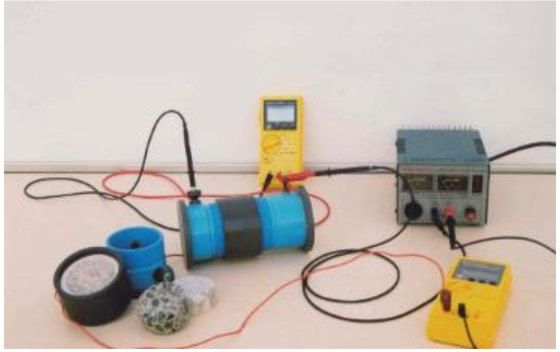


Rapid chloride migration test
NT Build 492



Rapid chloride permeability test

Wenner four probe

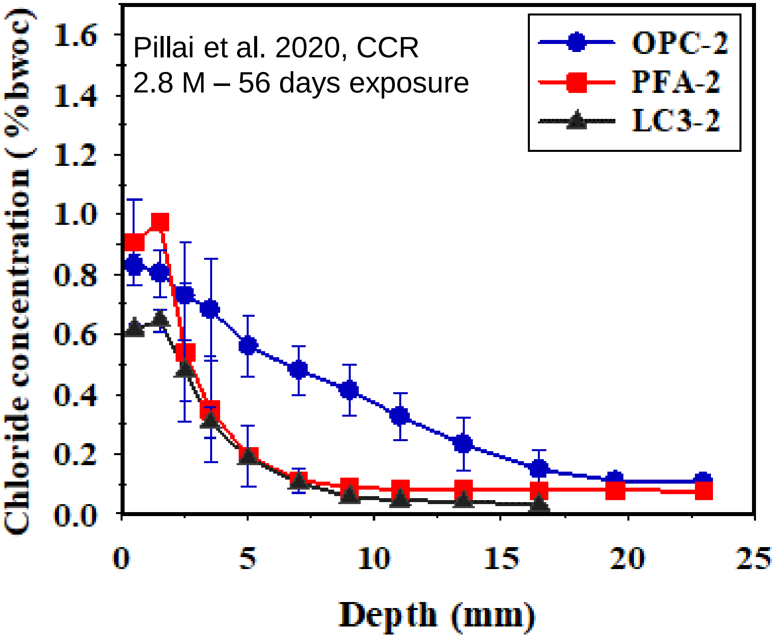


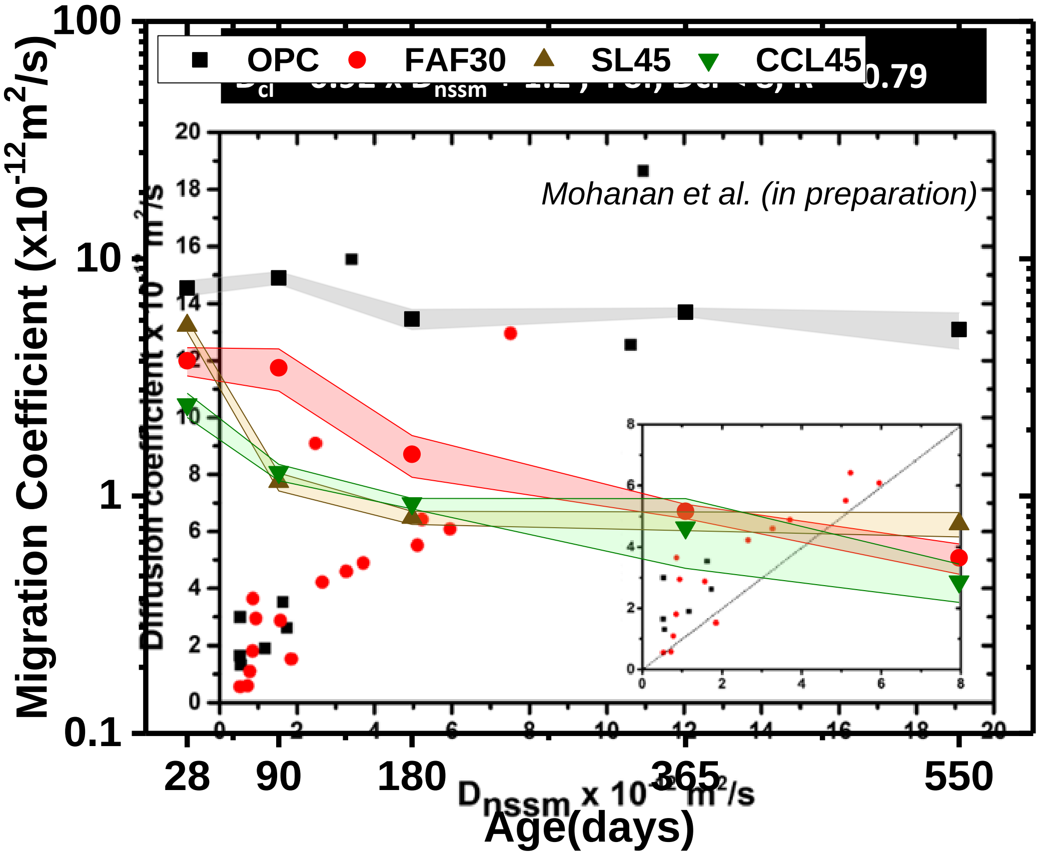
chloride conductivity test setup

H. Beushausen et al (2016)

Some images sourced from Dhanya, PhD Thesis, IIT Madras

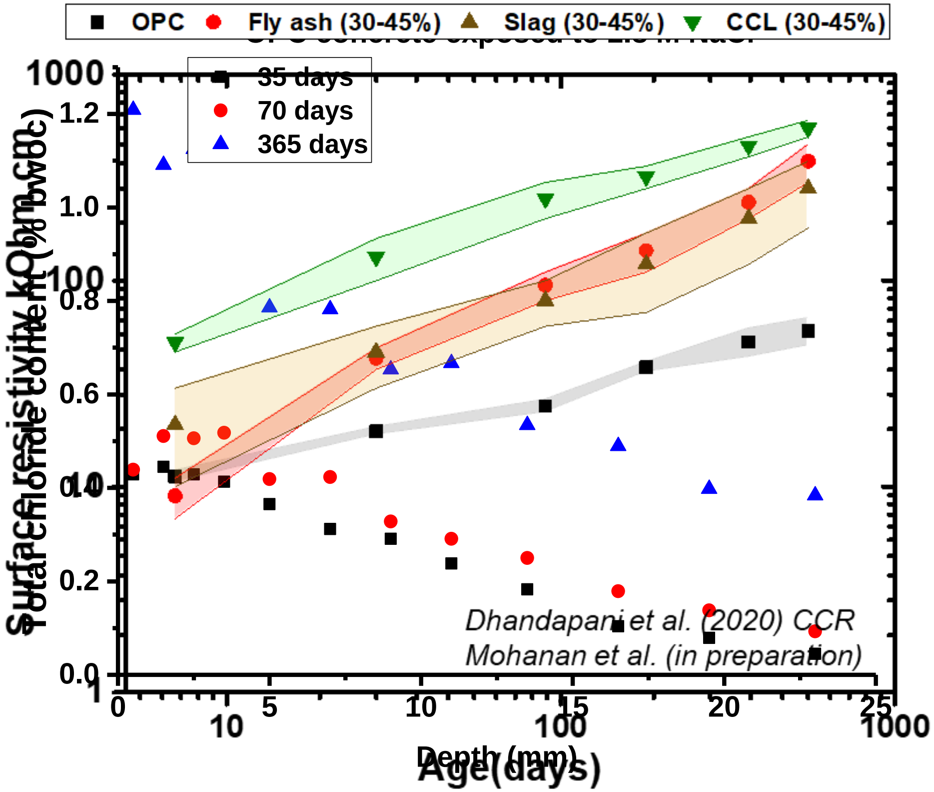
Influence of mineral admixture on chloride transport

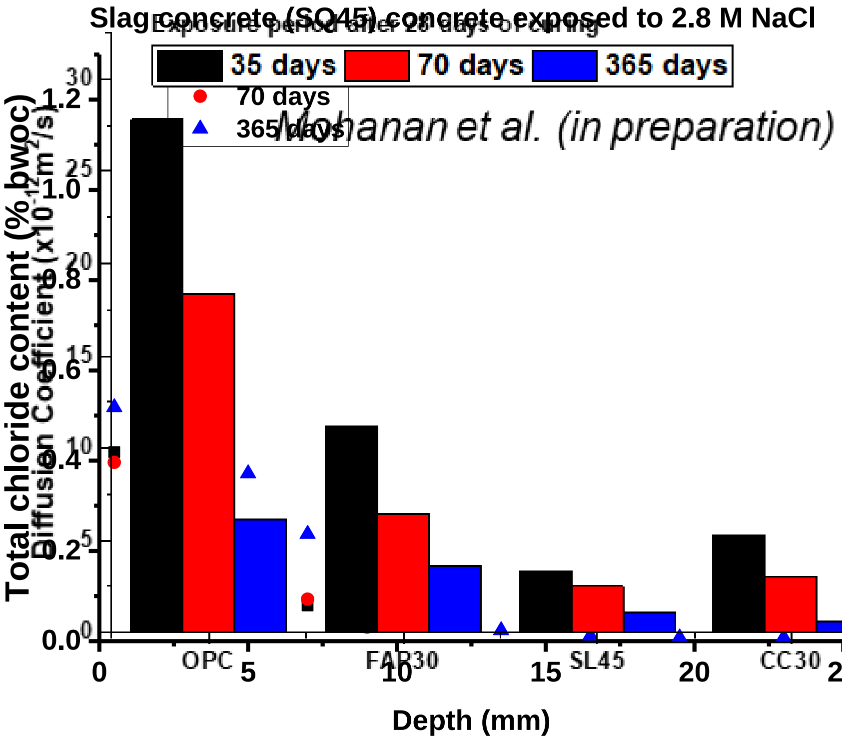




- Chloride transport parameter continues to reduce up to 2 years (and even beyond !) in blended binders with SCMs (Mohanan et al. in preparation)
- Accelerated chloride migration is a reliable measure to estimate Dcl as adopted in FIB 34

Lower chloride ingress rate in concretes with SCMs

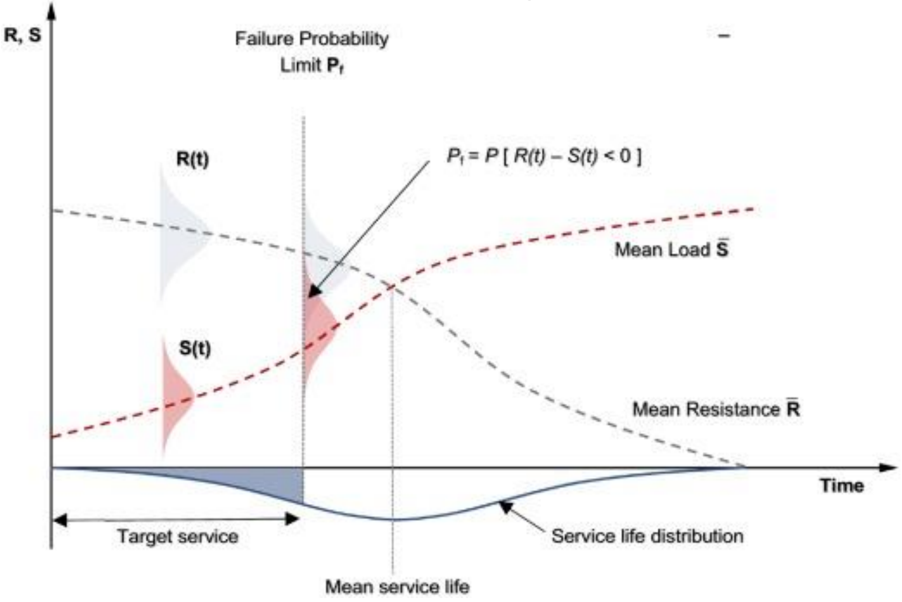


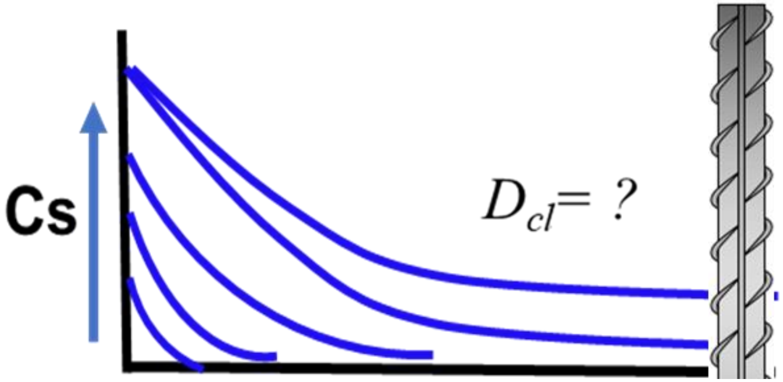


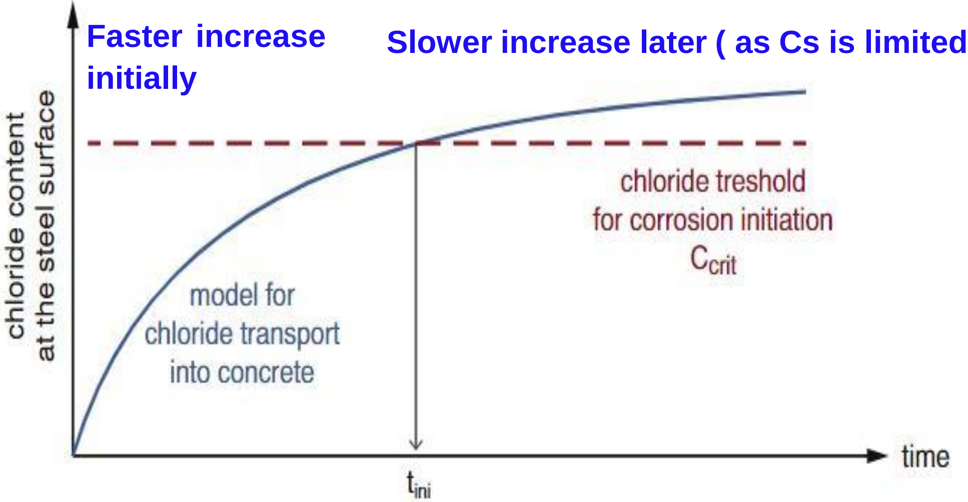
- Presence of SCMs significantly lowers diffusion coefficient – positive for reducing the tendency of chloride induced corrosion
- Continuous increase in resistivity due to the presence of SCMs – better resistance against ionic movement and refinement of pore structure

Chloride transport controls chloride build-up at the steel surface

ISO 13823:2008
General principles on the design of structures for durability







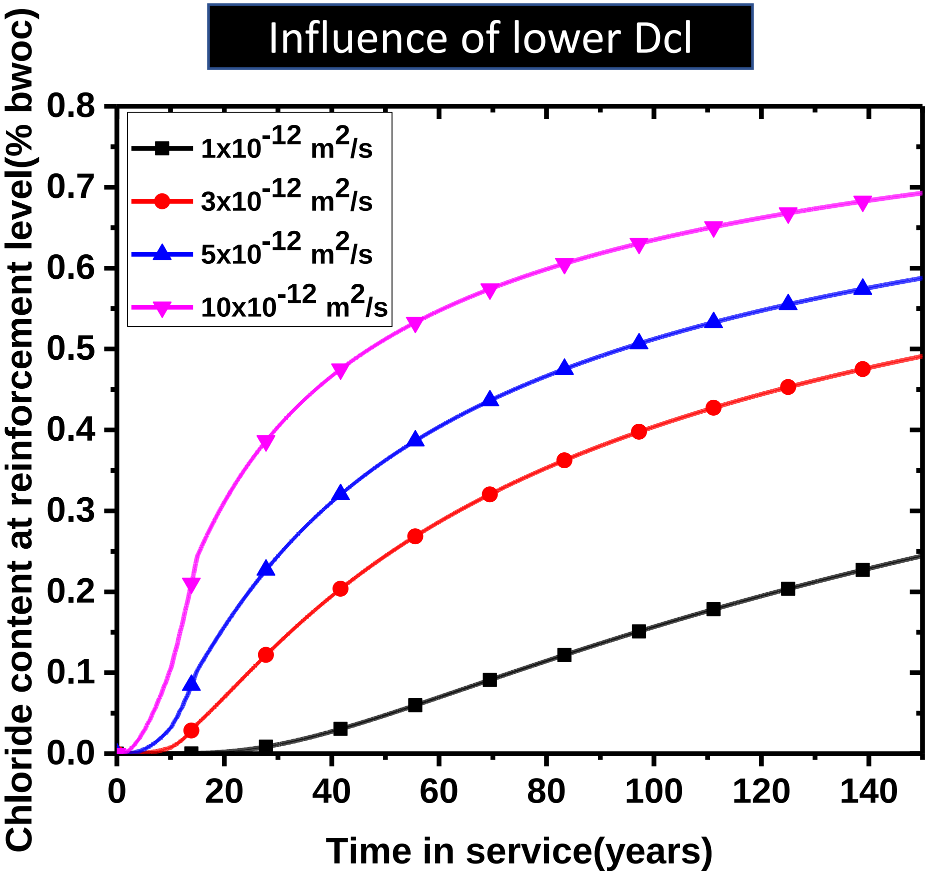
Faster increase initially

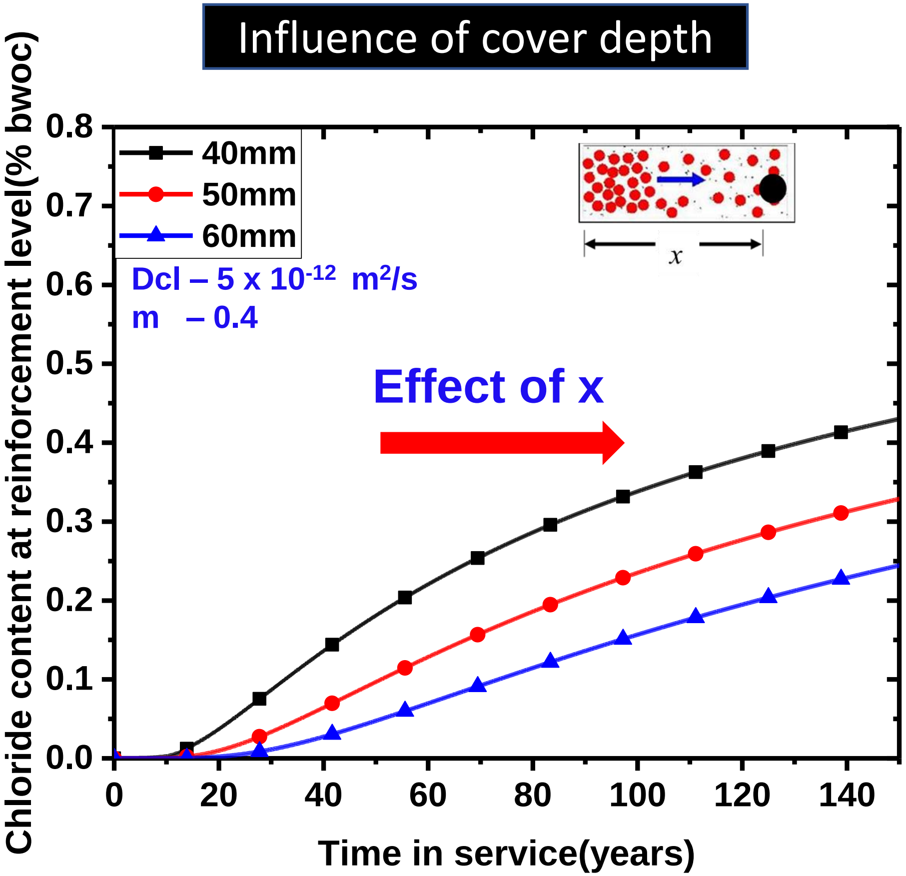
Slower increase later (as Cs is limited)

Angst et al. 2019

Concrete designed with consideration of transport parameter can have lower rate of chloride buildup at the surface of steel

Importance of chloride ingress rate

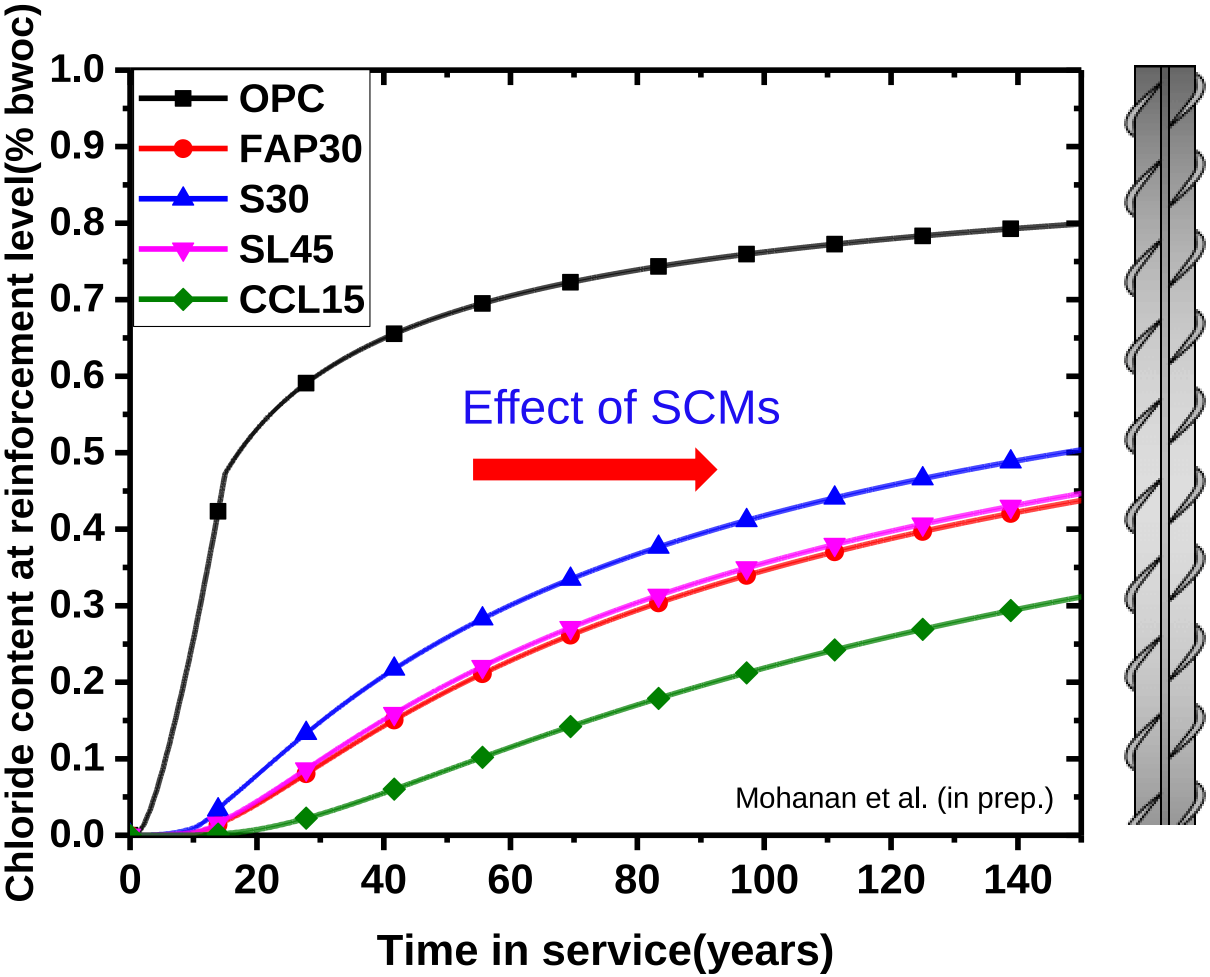

Influence of lower Dcl


Influence of cover depth

Lower diffusion coefficient – chlorides take more time to reach the surface of steel

Proper provision of concrete cover can further reduce the chloride build up rate along with reducing Dcl by the use of SCMs

Effect of SCM addition on transport of chlorides to steel surface



Effect of SCMs

Mohanan et al. (in prep.)

Holistic approach on the impact of SCMs in essential

- Lower diffusion coefficient
- Higher ageing coefficient

}

Limits chloride build up at steel surface

Transport prediction based on available chloride profile from a concrete structure

- Suppose you investigate an existing structure and study the chloride penetration profile
- Can we predict chloride ingress from the current performance levels in the field conditions?

Conservation of mass

$$\frac{\partial(\phi C)}{\partial t} + (1-\phi)\rho_c \frac{\partial C_b}{\partial t} = -\frac{\partial J}{\partial x} = D_{eff} \frac{\partial}{\partial x}\left(\frac{\partial C}{\partial x}\right)$$

Chloride binding

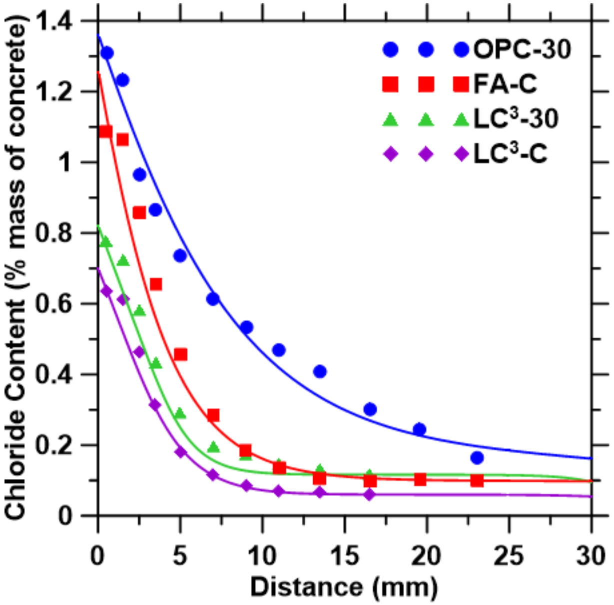
$$C_b = k_b C^m$$

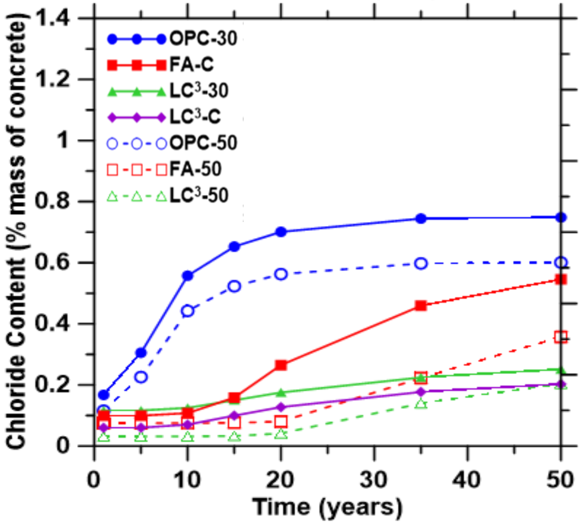
Effective diffusion coefficient

$$D_{eff} = \frac{\phi}{\tau^2}\frac{\lambda_i}{\lambda_i^0} D_{inf}$$

- Using Solver to the above equation with a boundary condition, validate by fitting the chloride profile. Add concrete properties like porosity, resistivity and bound/free chloride amount
- Then, simulation can predict the chloride ingress for the remaining extended exposure in the condition
- Blended cements have better resistance to chloride ingress due to lower porosity, refined pore structure and lower conductivity

Example: Consider a profile obtained after some exposure (here it's a lab data)





Pu Yang, Yuvaraj Dhandapani, Manu Santhanam, Narayanan Neithalath, ***Simulation of chloride diffusion in fly ash and limestone-calcined clay cement (LC3) concretes and the influence of damage on service-life (2020),*** *Cement and Concrete Research, Vol 130, 106010.*

Summary

- A transition from prescriptive to performance-based specifications requires fundamental understanding of the benefits from SCMs based on the governing transport process
- A combination of factors control chloride transport in concrete systems
  - Porosity, pore structure, resistivity and chloride binding
- In general, use of SCMs is significantly beneficial in improving chloride resistance of concrete mixtures
  - Calcined clay and slag concrete attain better chloride resistance at an early curing period
- A proper consideration to chloride ingress rate and ageing coefficient is essential to assess the complete potential of the concrete
  - Blended cements continuously evolve; unlike OPC systems
- The major impact of the SCMs can be distinguished by analyzing reduction of the buildup of chlorides at steel surface

Extensive work carried out at IIT Madras for several years on concrete durability – Some key references used here

- Alexander, M., Ballim, Y., and Santhanam, M. (2005). “Performance specifications for concrete using the durability index approach.” Indian Concrete Journal, 79(12), 41–46.
- Dhanya, B. S., and Santhanam, M. (2017). “Performance evaluation of rapid chloride permeability test in concretes with supplementary cementitious materials.” Materials and Structures, 50(1), 67.
- Dhanya, Santhanam M., Gettu R., Pillai (2018), Performance evaluation of concretes having different supplementary cementitious material dosages belonging to different strength ranges, Construction and building materials, Vol 187, pg 984-995
- Pillai, R. G., Gettu, R., Santhanam, M., Rengaraju, S., Dhandapani, Y., Rathnarajan, S., and Basavaraj, A. S. (2019). “Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3).” Cement and Concrete Research, 118(July), 111–119.
- Yuvaraj Dhandapani, Sakthivel Thangavel, Manu Santhanam, Ravindra Gettu and Radhakrishna G. Pillai, Mechanical properties and Durability performance of concretes with Limestone calcined clay cement, (2018), Cement and Concrete Research, 107, 135-152.
- Yuvaraj Dhandapani, Manu Santhanam, Investigation on the microstructure-related characteristics to elucidate performance of composite cements with limestone-calcined clay combination (2020), Cement and Concrete Research, Vol 129, 105959.
- Pu Yang, Yuvaraj Dhandapani, Manu Santhanam, Narayanan Neithalath, Simulation of chloride diffusion in fly ash and limestone-calcined clay cement (LC3) concretes and the influence of damage on service-life (2020), Cement and Concrete Research, Vol 130, pg 106010.
- Yuvaraj Dhandapani, Manu Santhanam, Ravindra Gettu, and Radhakrishna Pillai, Perspectives on Blended Cementitious Systems with Calcined Clay-Limestone Combination for Sustainable Low Carbon Cement Transition (2020), Indian Concrete Journal, Feb 2020, pg 31-45.

- Several other publications from IITM construction materials research group and elsewhere around the world are acknowledged. . .

Thank you…
I will be happy to take your questions