Diffusion of chloride from seawater into the concrete analysis: a literature review on implemented approaches

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Abstract. Infrastructures near the sea, such as ports, offshore platforms, bridges, and coastal buildings, are affected by seawater due to the coastal region. Chloride, contained in seawater, causes a decrease in the strength and durability of the concrete. Some researchers have published a paper on analyzing the penetration of chloride ions into concrete under different coastal environments and predicted chloride diffusion in concrete with computational modeling. This paper aims to review the existing literature related to various laboratory work tests and analytical methods in evaluating the diffusion of chloride from seawater into concrete. A set of forty papers were collected and reviewed that were published from 2011 until 2020 for studying. The review showed that chloride diffusion was a complex process and affected by many factors such as material properties, curing time, immersion/exposure time, and environmental conditions. Various experimental methods in the Laboratory were conducted using concrete specimens made from various materials in the exposed and submerged conditions. Researches in the field were carried out on existing structures with a certain building age using non-destructive testing. Meanwhile, the analytical methods applied simple equations and numerical simulation computational software.

keywords: chloride diffusion, concrete analysis, literature review

1. Introduction

Concrete is the most used material in the construction industry worldwide. Built concrete infrastructure is exposed to specific environmental conditions during the asset life, which imposes chemical and physical actions that may lead to premature deterioration. Poor concrete durability and corrosion of reinforcement bars are the primary cause of structural deterioration and reduced service life. Most concrete deterioration mechanisms are driven by transport properties, in particular, the chloride diffusion coefficient. [1]

Chloride ingress into concrete is the most critical factor affecting the durability of the concrete structure due to its causes steel reinforcement corrosion embedded in concrete causes of chlorides in actual concrete structures are splash and tidal action of seawater, airborne salt from the sea, dicing agent, and initially induced chloride with sea sand [2] [3].
Controlling chloride ions diffusion in concrete has a significant improvement in the building material field. Concrete is composed of cement, aggregate, and paste interfacial zone. The larger the aggregate will affect on the smaller the diffusion coefficient [4]. The diffusion coefficient of concrete with a low water-cement ratio is relatively smaller than that with a high water-cement ratio [5].

Several aspects exist in chlorides penetration in concrete. The study related to the process, involved parameters, and its modeling are required. Study about the results from experimental work and analytical solution for chloride diffusivity in concrete, including the difference in the chloride diffusivity for different environmental conditions, cement types, and different water-cement ratios, are needed to explore available literature.

Estimation of surface chloride and diffusion coefficient in chloride ingress to the concrete surface and diffusion coefficient in concrete is necessary to predict service-life of concrete structures. In some studies, the relationship between environmental conditions and chloride ingress into concrete based on field affected various factors such as uncertain changes in environmental conditions (local climate, effect of rainfall), exposure time, and long-term change of concrete properties.

Research on the diffusion of chlorides has been carried out with various experimental and different mathematical analytical methods. Detailed knowledge of the chloride penetration To prevent loss in serviceability of concrete in a marine environment that results in corrosion damage in concrete is to be understood [6]. In synthesis, despite the Diffusion of Chloride studies, there is no review considering the state of the art of various experimental methods, mathematical analysis methods, and software application in modeling chloride diffusion equation in concrete that systematically explain the difference experimental laboratory works techniques in this field. So that, the authors want to explore the specifications, advantages, drawbacks, and accuracy of the methods. The current study aims to preview various experimental methods, mathematical analysis methods, and software applications in modeling chloride diffusion in concrete. The scope of this paper is limited to the diffusivity of chloride on concrete structures in a salty environment.

2. Material and Method

2.1. Review Data
Different methodologies of experimental and analytical methods of chloride diffusion were classified from reputed Journals from 2011 to 2020. Journals were selected based on aims, experiment type used, and mathematical/analytical methods used on chloride diffusion into concrete, especially on structure in the marine environment.

2.2. Chloride Diffusion Research
Chloride penetration in concrete, freezing and thawing, reinforcement corrosion in concrete, alkali-aggregate reaction, and carbonation are widely known as some deterioration mechanisms in concrete. Chloride penetration and reinforcement corrosion in concrete play an essential part. Reinforcement corrosion in reinforced concrete is either chloride-induced or carbonation-induced. In practice, some methods can be applied to estimate the chloride diffusivity: a diffusion cell type test, a rapid chloride permeability test, a ponding test, a wind tunnel test, or the chloride concentration profiles of different concrete.

2.3. Analysis Method
Fick’s diffusion equation is the commonly used formula to calculate the time-dependent chloride content in concrete. This equation empirically determined surface chloride content as a boundary condition, depending on the distance from the shoreline. Penetration of chloride ions into concrete is often modeled as a concentration gradient drove diffusion process with the formula: [2] [5] [6] [7] [8]

\[
\frac{\partial^2 C}{\partial x^2} = D \frac{\partial C}{\partial t}
\]

solution of the equation is solved by:
\[ C(x,t) = C_0 \left(1 - \text{erf} \frac{x}{\sqrt{4Dt}} \right) \]  \hspace{1cm} (2)

Where \( C(x,t) \) is the concentration of the chloride ions at a depth of \( x \) from the surface after a time \( t \) of exposure. \( C_0 \) is the surface chloride ion concentration, and \( D \) is the coefficient of diffusion of the concrete. The basis of this equation's formulation is that both \( C_0 \) and \( D \) are constants in this formulation, over time and at different locations of the concrete structure.

Use a computer statistical analysis program, and the nonlinear regression is carried out on the experimental data. By curve fitting of solutions of Fick's second law of diffusion, the values of \( D \) and \( C_s \) in the Eq. (2) are determined. The curve fitting has been done so that the chloride profiles are fitted where the correlation between the measured and fitted profiles has a maximum. Curve fitting has been performed following a procedure described in NordTest NT Build 443 and resulted in two regression parameters: a diffusion coefficient and surface chloride content [7]. Besides Fick's diffusion equation analysis method, there are some diffusion equation analysis methods such as Szwedda's equation which is based on the expression determining the diffusion coefficient of chloride ions \( D^1 = 1/\Omega \) – which is the reverse of the diffusion resistance of the entire tested concrete zone [9], Nernst–Einstein equation for porous materials such as concrete the diffusion coefficient formulation [10], Nernst–Planck equation numerical model based on the ionic coupling effects among ions in chloride solutions and ions in concrete pore solution, Na+, K+, OH- [11] and Bayesian inverse technique is used to estimate diffusion and migration coefficients of chloride in concrete treated as a saturated porous material [12].

3. Result and Discussion

3.1. Classification of Material Properties of Concrete

Factors of material properties thought to be influencing chloride diffusion in experimental works have been explored in several studies.

| Various materials used in Concrete Specimens |
|--------------------------------------------|
| **Normal concrete:**  | Cement, sand (fine aggregate), gravel (coarse aggregate), additive [2] |
|  | - Fly Ash (FA) [3] |
|  | - sand and glue [4] |
|  | - OPC, GGBS & CWA (GGBS: 20% and 40%) [5], |
| **Recycled concrete:**  | - fly ash and slag [6]. |
| - Crushed Coarse Aggregate (CCA) [13], | - NPC (with Normal PC) & SFC (with Silica Fume) [7] |
| - Recycled Coarse Aggregate (RAC) [14], | - OPC, FA & GGBS, GGBFs [15] |
| - Ceramic Waste Aggregate (CWA) mortars containing the Ground-Granulated Blast-furnace Slag (GGBS) 20% and 40% [5] | - High Early Strength Cement (HESC), fly ash, and an additional 20% of hydrated lime [16] |
| - aggregates content (0%, 20%, 30%, 40% and 50%) and bricks content (10%, 30%, 50% and 70%) [17] | - Alkali Activated Slag (AAS) concretes [18] |
|  | - Ground-Granulated Blast-Furnace Slag (GGBS) [13] |
|  | - OPC, Fly ash, Slag, Silicon powder [19] |
|  | - Fly Ash, the improvement of concrete impermeability by combining filling agent (F), water reducing agent (WR), fluorosilicate based agent (FB), and expansion agent (E) [20] |
|  | - Ordinary Portland Cement (OPC) & Fly Ash (FA) [21] |
|  | - fly ash, blast furnace slag, clay, nanocomposites, silica fume, Fuel ash, and meta-kaolin [23] |
|  | - concrete with and without silane-based surface treatment [25]: |
| **Types of aggregate:**  | - the crushed Basalt [12] |
| - the crushed limestone [11] | - NC and SCC mixtures [22], |
| - granite, [24] | - natural siliceous sand and gravel [25] |
|  | - cement Type: |
|  | - Water/cement (w/c) ratio |
| - CEM II 52.5 R [12] [25] | - w/c = 40% and 60% [2] [3] |
Various materials used in Concrete Specimens

- CP VR [26].
- OPC, HES, SCB*AL cement [3]
- OPC, CEM I and CEM III/A [27] [13]
- CEM I 42.5 R. CEM III/A 32.5 N-LH/HSR/NA, CEM I 42.5 N/SR3/NA, CEM IV/B (V) 32.5 R – LH/NA [27]
- PC equivalent to ASTM Type II [7]
- CEM I 42.5 N [24] and CEM III/A 42.5R [25]

Water/Binder (W/B) ratio: 
- W/B = 0.5 [3]
- W/B = 0.4, 0.5, and 0.6 [5]
- W/B = 35%, 45%, 55% [15],
- W/B = 0.47 [18]
- W/B = 0.4 and, 0.33 [24]

Aggregate/cement ratios: 4 – 6 [26]
- Fly ash – binder ratios: 0.2, 0.35, and 0.5 [3]

The volume fractions of coarse aggregate:
- v = 0, 0.2, 0.3, 0.4, and 0.5. [15]

3.2. Classification of Specimen of Concrete for Research
Recently, experimental works of chloride diffusion were established from a variety of sample and specimen types. Certain samples were used by some authors, mortar, concrete, drilling core of the existing concrete structure, and concrete powders.

3.3. Classification of Various type of Marine Zone and Influencing Factors of Concrete
In previous studies on chloride diffusion, different types of marine zone have been found to be related to chloride diffusion. Some studies modeled study in environment type: underwater area [5]; tidal area [7] [15]; splash area [32]; atmospheric area or airborne salt [2] [3] [33] [34]; tidal, submerge, atmospheric [22]; tidal area, splash area, atmospheric area [28] [35]; underwater area/submerge, tidal area, splash area, atmospheric area [19] [31] [36]; dry/fully/partially saturated condition (DCC/PSC/FSC) [29].

3.4. Classification of Independent and Dependent Variables
Among the reported studies, independent and dependent variables in experimental works are as shown in Table 2.

| Table 2. Independent and dependent variables in experimental works |
|---------------------------------------------------------------|
| **Independent Variables** | **Dependent Variables** |
| - material properties and mix proportional design of concrete: normal concrete, recycled concrete, cement type, type of aggregate, concrete with various type of portland cement, concrete with replacement/ substitute material, water/cement ratio, aggregate/cement ratio, or water/binder ratio, different mix proportions (in section 3.1), [2] [3] [4] [5] [6] [7] [11] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [24] [25] | - depth of chloride penetration, chloride content in concrete, diffusion coefficient of chloride, chloride profile in concrete [1] [2] [3] [4] [6] [17] [10] [11] [12] [15] [18] [19] [20] [22] [23] [25] [26] [28] [29] [30] [31] [34] |
| - curing time [1] [2] [3] [5] [7] [11] [15] [21] [25] [26] [29] | - the diffusion decay coefficients for chloride ions [15] |
| - Immersion time / ponding time / exposure time [5] [11] [12] [25] | - corrosion initiation time [11] [28] |
| - ambient temperature [6] [35] | - pore size distribution [11] [23] |
| - chloride solution [5] [11] [12] [25] | - the external hydraulic water intrusion [20] |
| - intensity of airborne salt [2] [3] | - the slump values [15] [18] [26] [29] |
| - concrete cover depth [3] [15] [28] [35] | - permeability [22], impermeability [20]; |
### Independent Variables
- depth of measuring chloride from exposed surface [2] [3] [19] [28] [29] [31]
- diameter of steel reinforcement [15]
- mechanical load [19]
- marine zone (in section 3.3)
- age of concrete [6] [17] [31], age factor [28]
- collect experimental data from other researchers/ literatures [17] [33] [34]
- location of element [36]
- de-icing salt [24]
- coated concrete structures (double-layered systems) [37]; hollow cylinder (six-layer cylinder) [4]
- wet-dry cycles [1] [32]
- water saturation degrees: 50%, 75%, 90% and 100%. [26]
- marine zone (in section 3.3)
- bulk electrical resistivity [10] [25]
- age of concrete [6] [17] [31], age factor [28]
- effect of cations [11]
- collect experimental data from other researchers/ literatures [17] [33] [34]
- a visual inspection of the structure to determine the structure's current condition and the nature of testing required. [36]
- hydration time [17]
- location of element [36]
- the effects of the corrosion inhibitor [18] [25];
- de-icing salt [24]
- coated concrete structures (double-layered systems) [37]; hollow cylinder (six-layer cylinder) [4]
- wet-dry cycles [1] [32]
- water saturation degrees: 50%, 75%, 90% and 100%. [26]
- collect experimental data from other researchers/ literatures [17] [33] [34]
- a visual inspection of the structure to determine the structure's current condition and the nature of testing required. [36]

### Dependent Variables
- compression strength [1] [3] [11] [15] [18] [20] [25] [26] [29] [30] [36]
- water absorption [20]
- reliability index [28]
- bulk electrical resistivity [10] [25]
- effect of cations [11]
- collect experimental data from other researchers/ literatures [17] [33] [34]
- a visual inspection of the structure to determine the structure's current condition and the nature of testing required. [36]
- the properties of the corrosion inhibitor [18] [25];
- air content [15] [25]
- the result of RCPT [6] [10] [13] [16]
- the stress influence coefficient [38];
- service life prediction [30] [31]

### 3.5. Classification of Experimental Methods
A multitude of tests has been proposed and applied to test the concrete resistance to chloride diffusion. Some experimental methods for Chloride Diffusion and Steel Reinforcement Corrosion Test were used in the previous study are shown in Table 3. In addition, it is necessary to carry out tests to determine the physical, mechanical, and chemical properties of concrete that are thought to affect the diffusion of chloride.

#### Table 3. Experimental methods for chloride diffusion and steel reinforcement corrosion tests

| Test of Physical, Mechanical, and Chemical Properties of Concrete | Test of Chloride Diffusion and Steel Corrosion |
|---------------------------------------------------------------|------------------------------------------------|
| - specific gravity [5] [11] [25]                               | - RCPT [6] [10] [13] [16]                           |
| - density [16] [26]                                            | - wind tunnel test [2] [3].                         |
| - slump value [15] [18] [26] [29]                             | - thermodynamic migration model [12]               |
| - flow table test [25]                                        | - chemical analysis by an argentometric titration [12] |
| - tensile strength [1] [3]                                     | - potentiometric titration [26]                    |
| - compressive strength [1] [3] [15] [18] [20] [25] [26] [29] [36] | - the artificial marine tidal environment automatic simulation device and an electrophoresis experiment [15] |
| - mercury intrusion porosimetry (MIP) tests [26]               | - chloride migration test/bulk diffusion test (NordTest Build 492 & 443) [7] [12] [13] [18] [25] |
| - pore structure [5] [16] [23]                                 | - petrographic examination and mapping of chloride profiles [24] |
| - water absorption [20]                                       | - the rapid chloride test method (RCM) [14]        |
| - air content [15] [25]                                        | - natural chloride diffusion test [25]            |
| - a visual inspection on structure [36]                        | - an electron probe microanalysis (EPMA) [5]       |
| - X-ray diffraction [16],                                     | - salt ponding test (AASHTO T259) [18] [29]       |
| - permeability/impermeability [20] [22]                        | - pressure penetration [19]                        |
| - electrochemical impedance spectroscopy [1]                  | - on-site measurement of concrete resistivity, using the Wenner probe measurement or 4-point method (AASHTO TP 95) [36] |
| - the carbonation depth measurement test [3]                   | - to determine the level of chloride ingress on the structure Half-cell potential, HCP (ASTM C876) [3] [36] |
| - chemical analysis of seawater [36]                           | - measurement of the rate of reinforcement corrosion on the existing quay structure (ASTM G1 – 03) [36] |
The literature on chloride diffusion has presented several experimental methods for chloride diffusion and steel reinforcement corrosion. Otherwise, chloride diffusion is a complicated and multi-mechanistic phenomenon. Each testing limitation is important to understand in reinforced concrete design consideration.

Although the findings should be interpreted with caution from various studies, this study has listed some results from current studies regarding chloride diffusion analysis.

| Authors                  | Aims                                                                 | Methods                                                                 | Results                                                                 |
|--------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Nuralinah et al. [2]     | To investigate the relationship between the intensity of airborne salt and surface chloride content based on the test results obtained by the developed testing equipment. | - By wind tunnel test  
- Analyzed by several computational models | - The airborne salt intensity affected the content of surface chloride in the concrete.  
- Chloride ingress analysis based on constant diffusion coefficient overestimates long-term chloride content in concrete. Meanwhile, based on time-dependent diffusion coefficient estimates long-term chloride profiles better than constant diffusion coefficient. Using time-dependent surface chloride as a boundary condition results in better estimation of chloride profiles early than constant surface chloride. Meanwhile, both short and long-term chloride profiles are a good estimate based on time-dependent diffusion coefficient and time-dependent surface chloride prediction. |
| Zeng, L. and Song, R [4] | To report how six multilayer concrete can cloak chloride ions        | - Measuring the concentration of chloride ions by NJCL Chloride Ions Concentration Fast Measurement Equipment.  
- The numerical simulation used COMSOL Multiphysics software. | - The six-layer mass diffusion cloak could protect concrete against chloride ions penetration.  
- The concentration gradients were different in the inside and outside the outer circle in the diffusion flux lines  
- In an ideal mass diffusion cloak, the diffusion matters do not penetrate the inner circle. |
| Higashiyama et al. [5]   | To investigate the apparent chloride diffusion coefficient and the pore size distribution of CWA mortars containing the GGBS at 48 and 96 weeks immersion | - use an electron probe microanalysis (EPMA) and a mercury intrusion porosimetry at each immersion time.  
- The chemical and physical properties of these materials are observed | - The chloride diffusion coefficient depends on time and is related to a ratio of water-cement.  
- Chloride diffusion in the CWA mortar was reduced by GGBS usage.  
- Chloride diffusion was controlled by cumulative pore volume |
| Paul et al. [6]          | Analysis of the diffusion process in OPC concrete mix resulted in     | - by using RCPT (ASTM 1202)                                              | With fly ash replaced, some quantity of an OPC concrete mix resulted in |
| Authors | Aims | Methods | Results |
|---------|------|---------|---------|
| Khanzadeh-Moradllo et al. [7] | To investigate the effect of wet curing duration on chloride penetration in plain and blended cement concretes with 7.5% silica fume subjected to tidal exposure conditions in the Persian Gulf for five years. | - Testing for chloride penetration in the field (exposure to seawater) - Analyzed using Fick's second law of diffusion equation | - Diffusion coefficients affected by wet curing extension due to its improvement in the quality of concrete cover to block the ingress. - Surface chloride content in The Silicafume concrete (SFC) specimens’ comparison with Normal Portland Cement concrete (NPC) specimens are different increment changes over time. |
| Dodds et al. [13] | To investigate the effects of three sources of coarse CCA (Crushed Concrete Aggregates) from known structural elements on the rapid chloride migration coefficient and accelerated time to corrosion initiation and to crack of structural concrete. | - Rapid chloride migration test used to measure rapid chloride migration coefficient (Dnssm) - accelerated corrosion test was done according to NT Build 492 and 356 | The chloride ion ingress of structural concrete was affected by coarse CCA. However, the inclusion of GGBS (Ground Granulated Blast furnace Slag) to produce structural CEM III/A concretes and allowing higher proportions of coarse CCA could mitigate these effects |
| Lu, G. et al. [17] | To establish the numerical simulation method for the distribution of chloride ion concentration based on the similarity of the two-dimensional heat conduction theory of | - CI diffusion Equation use Fick Second Diffusion Law. - Build a Random Aggregate Model of Recycled Concrete in ANSYS - The PLANE55 | The chloride concentration distribution was non-uniform within the recycled aggregate concrete and declined along with diffusion depth. Therefore, to improve the durability of recycled concrete, in recycled concrete production was necessary to separate the discarded bricks |
| Authors          | Aims                                                                 | Methods                                                                 | Results                                                                                                                                 |
|------------------|----------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Lei et al. [19]  | - To investigate lining concrete durability                          | - Adopts existing research results (Pressure Penetration Test)         | Especially in shallow areas, the chloride diffusion model considering the linear stress distribution on a sectional structure reflected the effects of linear stress distribution of the sectional structure on chloride diffusivity. |
|                  | - To derive a modified chloride diffusion model for concrete based on the odd continuation of boundary conditions and Fourier transform | - derive a modified chloride diffusion model for concrete based on the odd continuation of boundary conditions and Fourier transform. |                                                                                                                                          |
| Jung et al. [21] | Evaluate of crack and time effect on the chloride diffusion rate.    | - RCPT (ASTM 1202)                                                    | Crack width influences on diffusion coefficients as long as the curing period of concrete                                              |
| Nosratzehi et al. [22] | To investigate chloride penetration and mechanical properties of self-compacting concrete and normal concrete under different environmental conditions in Chabahar Port, located in southeastern Iran, north of the Oman Sea. | - Concrete was exposed to various environmental conditions such as tide, submersion, and atmospheric conditions. - Use bulk diffusion test (NT Build 443) - the concentration of chloride determines with powder making and titration test. - The diffusion coefficient Dc and the surface chloride Cs values were obtained using the fitting toolbox of Matlab. | The values of surface chloride and diffusion coefficient in submersion conditions showed better performance on SCC, for a given water-to-cement ratio, the self-compacting concrete (SCC) has higher durability compared to normal concrete (NC) |
| Szweda et al. [27] | Describe tests on the protective properties of the concrete cover made of ordinary concrete and different types of low alkali cement. | - By migration tests in the electric field                               | - The base material of concrete is highly related to protection ability against chloride ions penetration. - In an aggressive environment, i.e., sulfate corrosion, it is best to use blast furnace cement in exposed construction. |
| Wu et al. [28]   | - To study the effects of exposure conditions (atmospheric, tidal, and splash zones) on chloride ingress into concrete and time-dependent chloride | - The chloride concentration was determined by RCT (Rapid Chloride Concentration Tester). - To describe chloride penetration in | At the same corrosion depth, the chloride concentration in the splash, tidal and atmospheric zones are dependent on the weight of concrete. The durability of concrete structures was affected by the splash zone more harshly than tidal and atmospheric |
| Authors          | Aims                                                                 | Methods                                             | Results                                                                 |
|------------------|-----------------------------------------------------------------------|-----------------------------------------------------|-------------------------------------------------------------------------|
|                  | diffusivity of concrete.                                               | concrete, using Fick's second law                   | zones. The DuraCrete 2000 model could better characterize the chloride transport in the tested concrete compared with the Life 365 model and the LNEC E465 model, |
|                  | - To obtain a reasonable model through comparative analysis of three calculation models to predict the initial time of reinforcement corrosion. | - the purposed model compared with Life 365, LNEC E465, DuraCrete 2000. |                                                                         |
| Balakrishna et al. [29] | To examine the influence of conditioning (dry/fully/partially saturated) on the results of chloride concentration at different drill depths (30-40-50 mm) in concrete slabs with different mixtures proportion in which slump and w/c ratio value was varied with constant compressive strength as in the first case and compressive strength, and w/c ratio value varied with a constant slump as in the second case. | - The unidirectional salt ponding was adopted as per [AASHTO T 259] method. - Volhard's method was used for the determination of the total chloride content in the concrete. - The average chloride concentration was decreased insolvent/water-based impregnation DCC/PSC/FSC (dry/partially/fully saturated conditioned concrete) slabs compared to control DCC/PSC/FSC slabs for a constant higher level compressive strength and varied slump value as well as varied compressive strength and constant slump value. - Chloride concentration was correlated with different drill depths by power type of equation in preconditioned (DCC/FSC/PSC) control/impregnation concrete slabs |                                                                         |
| Yang et al. [33]  | To develop an improved computational model for the surface chloride concentration of concrete exposed to the marine atmosphere zone by considering environmental conditions and material parameters. | - Fick's second law of diffusion obtains the surface chloride concentration of concrete. - An improved computational model was proposed to estimate the surface chloride concentration - The accuracy and applicability of this model were validated by comparing it with current computational models (DuraCrete, LNEC & McGee Model) and field investigation data. | 1. The transportation process was divided into two stages: airborne chloride salt deposition on the external surface of concrete and penetration of chloride ions into bulk concrete. 2. The proposed model is consistent with the transportation and accumulation of chloride ions from sea air into bulk concrete. 3. The surface chloride concentration of concrete was affected by distance from the coast, water-to-binder ratio, exposure time, and wind speed. |
| Yu, F. et al. [35] | To study the influences of the variability on boundary chloride concentration, the | - Use Fick's second law to describe the free chloride concentration evolution in concrete. | 1. Thicker concrete cover and higher concrete strength resulted in a higher diffusion coefficient. 2. Concrete cover thickness |
| Authors          | Aims                                                                 | Methods                                                                 |
|-----------------|----------------------------------------------------------------------|------------------------------------------------------------------------|
| thickness of the concrete cover, and chloride diffusion coefficient on corrosion initiation of reinforcing steel. cumulative distribution | The Monte Carlo simulation in the prediction of the corrosion initiation of reinforcing cumulative steel distribution. A finite element model was established to calculate corrosion initiation time. Kriging model was constructed based on the toolbox "DACE" of MATLAB software. |
| Osuji et al.    | - Evaluate the extent of deterioration of an existing 45 years old concrete quay structure. - Investigation chloride-induced reinforcement corrosion. | 1. Visual inspection of the structure 2. Chemical testing of the available seawater in the region 3. Non-destructive testing (Compressive strength, Concrete resistivity, Half-cell potential (HCP), corrosion current density/corrosion rate of steel reinforcement, Chloride content/chloride diffusion coefficient ). |
| Wang et al.     | - To explore and discuss the coupling effects of coarse aggregate and steel reinforcement on chloride transport in concrete - The findings are expected to be useful in realistically predicting the durability of reinforced concrete structures. | - Simulating the marine environment in a diurnal tidal zone, the artificial marine tidal environment automatic simulation device developed by the research team of Harbour Engineering Structure Laboratory in Tianjin University is used to simulate the real-time tidal cycles realistically. - Use the coarse aggregate volume fraction impact factors, the direct and indirect blocking effect coefficients of rebar. - To improve the analytical solution of Fick's second law, a prediction model of the blocking effects of steel bar enhanced the chloride concentrations at the surface of rebar significantly. The surface chloride concentration was independent of coarse aggregate effects. However, the apparent chloride diffusion coefficients were affected by the exposure time. The impact factor of coarse aggregate volume fraction f(v) was adopted to improve the chloride diffusion coefficient within the analytical solution of Fick's second law and proposed to quantify the effect of coarse aggregate on chloride diffusion coefficient. |
chloride diffusion in concrete considering the coupling effects of coarse aggregate and steel reinforcement

| Authors          | Aims                                                                 | Methods | Results                                                                 |
|------------------|----------------------------------------------------------------------|---------|------------------------------------------------------------------------|
| Farahani et al. [40] | The Element-Free Galerkin (EFG) method is employed to solve the diffusion equation, and the results are compared to Finite Element Method (FEM), Finite Difference Method (FDM), and analytical method in special cases. | - Fick's second law of diffusion is the dominant equation to modeling the diffusion of chloride ions. This equation is solved by the Finite Element Method (FEM) and Finite Difference Method (FDM).  
- This study solves Fick's equation using the Element-Free Galerkin (EFG) method and FEM and FDM. The results of these numerical methods are compared together and validated with the analytical solution. | The EFG method predicts the service life of the concrete structures more accurately than the other methods. It exhibits the lowest displacement error and energy error for a constant diffusion coefficient problem. FDM can be performed very efficiently for simple models, and the displacement errors produced by this method do not differ considerably from the EFG results. Therefore, FDM could compete with the EFG method in simple geometries. FEM can be used with a sufficient number of elements while the convergence of the results should be controlled. However, in complicated models, FEM and especially the EFG method are much more flexible than FDM. |

Chloride diffusion and corrosion models can be validated and verified by the advanced computational capabilities and special and general-purpose software availability. In addition, these types of software can be used for performing parametric studies to determine the most factors that affect the service life of concrete structures.

4. Conclusions
The main goal of the current study was to review the existing literature related to various laboratory work tests and analytical methods in evaluating the diffusion of chloride from seawater into concrete. According to the studies analyzed in this paper, the finding of the review study has concluded in the following:

- Various factors are used in research to analyze the effect of these factors on the diffusion of chloride into the concrete, including material properties, marine zone, curing time, immersion/exposure time, the intensity of airborne salt, the intensity of chloride solution for immersing, ambient temperature, water saturation degrees of concrete, concrete cover depth, depth of measuring chloride from the exposed surface, the diameter of steel reinforcement, age of concrete, mechanical load, location of the concrete element, and environmental conditions.
- Highlighted all available constructs of independent and dependent variables, measurable parameters, and measurement methods were explained in this paper.
- Some of the experimental methods were applied to measure chloride diffusion and corrosion of steel reinforcement: RCPT, wind tunnel test, thermodynamic migration, argentometric titration, potentiometric titration, the artificial marine tidal environment automatic simulation device, chloride migration test/diffusion test, petrographic examination, RCM, natural chloride diffusion test, an electron probe microanalysis (EPMA), salt ponding test, pressure penetration, Wenner probe measurement, Half-cell potential (HCP), electrical resistivity, the nature of corrosion, and measurement of the rate of reinforcement corrosion.
• Fick's second law and Crank's solution mathematical equation were adopted by a majority of the researchers in the analysis of chloride diffusion.

• The Finite Difference Method (FDM) can be performed very efficiently for simple models to solve the diffusion equation. The finite Element Method (FEM) can be used with a sufficient number of elements. At the same time, the convergence of the results should be controlled. However, FEM and Element-Free Galerkin (EFG) methods are more flexible in complicated models than FDM.

• Numerical simulation of chloride diffusion can be done with computational software. MATLAB, COMSOL, ANSYS, STADIUM, Life-365 were the commonly computational method used by various authors. The software was applied due to its advancement in computational capabilities of chloride diffusion and reinforcement corrosion analyzing with a higher degree of accuracy.

• Several authors developed prediction diffusion models of concrete in the marine atmosphere zone by considering environmental conditions and material properties to derive a modified chloride diffusion model.

This work contributes to existing knowledge of concrete diffusion methodologies by reviewing current experimental methodologies, including recently discovered materials, methods, and diffusion models from journals of the last decade. The information presented in this paper could be useful for researchers in related fields to develop and extend the latest methodologies of estimating chloride diffusion and time for initiation in the corrosion process of steel reinforcement.

Analysis of chloride diffusion is useful in designing buildings in marine environments, such as determining the thickness of the concrete cover, estimating the initial time of steel reinforcement corrosion and cracking, and predicting the structure service life.

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