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**THEORETICAL EXAMINATION OF CHLORIDE INGRESS IN
REINFORCED CONCRETE STRUCTURES EXPOSED TO
CHLORIDE ENVIRONMENT CONDITIONS AND CLIMATE
CHANGES**

A Thesis

*Submitted to the College of Engineering / University of Babylon in Partial
Fulfillment of the Requirements for the Degree of Higher Diploma in
Engineering /Civil Engineering / Construction Material*

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

" يُدَبِّرُ الْأَمْرَ مِنَ السَّمَاءِ إِلَى الْأَرْضِ "

صدق الله العلي العظيم

(سورة السجدة الآية 5)

Certificate

I certify that this study entitled (**Theoretical Examination of Chloride Ingress in Reinforced Concrete Structures Exposed to Chloride Environment Conditions and Climate Changes**) is prepared by "**Ruaa Hasan Rasool Ismael**" under my supervision at the College of Engineering, University of Babylon in partial fulfillment of the requirements for the degree of Higher Diploma in Civil Engineering / **Construction Material**.

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Date: / 6 /2022

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Ruaa Hasan Rasool Ismael

2022

Abstract

Predicting service life is considered one of the most important issues in concrete structure design presently. durability design must be based on reliable modelThe ds that can more correctly characterize the deteriorating mechanisms. Concrete has become one of the most popular construction concepts in the world due to its unique combination of steel and concrete. However, a lack of information about concrete's long-term performance and the severity of environmental effects has resulted in major problems. Where, the penetration of harmful substances is significantly vital. Chloride attack is a major factor that affects the durability of concrete structures during their service lives. It has the potential cause to steel corrosion as well as concrete cover cracking and deterioration. Chloride ions can penetrate concrete by a variety of external sources, including de-icing salt, seawater, and salts concentration in groundwater. While, the materials used in the production of concrete are polluted such as the fine and coarse aggregate.....etc.

The goal of this research is to develop an integrated model that accounts several factors that influence chloride penetration in reinforced concrete structures, including external factors such as temperature, humidity, and internal factors which is represented by concrete properties such as the water-to-cement ratio, the replacement of part of the cement with supplementary cementitious materials and crack width.

The finite element approach was utilized in this work to find a model and estimate the chloride concentration with depth and time ($C(x,t)$) in Reinforced Concrete structures in this work by using package called commercially, COMSOL Multiphysics (5th Version).

Several previous investigations were employed to verify and evaluate the proposed model, and when comparing the results, it was found a convergence and correlation regression of not less than 83 %, which is within a good limits. The model was applied in a variety of studies, including changes in the water-cement ratio, humidity, crack width, the use of supplementary cementitious materials, as well as Intergovernmental Panel on Climate Change, IPCC, 2014 scenarios that take into account the effects of climate change.

Concrete structures that were estimated were also used with the proposed model, according to environmental exposure, it was applied to two reinforced concrete structures, one is built in the Basra City in 2020: a pier in Shat Alarab with a water-cement ratio of 0.5 exposure to seawater, and other case, culvert structure in AL-Najaf City with a water-cement ratio of 0.4 based about 1.5 m from the surface exposure to groundwater level. According to the IPCC, 2014, the temperature exceeded 4°C in the 2100 year in two scenarios where the model was used with time exposures of 25 and 50 years. The result show, at the time of exposure 50 years, the chloride content concentration propagates with an increase in temperature, and the exposure period is longer than the chloride content concentrations at the time of exposure 25 years.

The outcome of this research is supported with previous research, which found that as temperature, crack width, water-cement ratio, and relative humidity rise, chloride penetration in concrete increases, potentially causing corrosion in reinforced steel bars on the other hand. Using an supplementary cementitious materials could slow down the deterioration of concrete structures by increasing resistance of the chloride penetration.

Finally, the developed integrated model corresponds with current research results and theories, and so can be used to forecast chloride penetration and service life of reinforced concrete structures.

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List of Notation

Notation	Description
IPCC	Intergovernmental Panel on Climate Change
RCS	Reinforced Concrete Structures
FTIA	Finnish Transport Infrastructure Agency
pH	Potential of Hydrogen (Acid Indicator)
RCP	Representative Concentration Pathway
AR-5	Fifth Assessment Report
D_a	Diffusion Coefficient
C_s	Surface Concentration
C_{cl^-}	Chloride Concentration
$D_{a_{cl^-}}$	Diffusion Coefficient of Chloride Ions
SF	Silica Fume
FA	Fly Ash
SG	Blast Furnaces Slag
GGBS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gases
W_c	Crack width
$C_{s_{cl^-}}$	Surface Concentration of Chloride Ions
OPC	Ordinary Portland Cement
$C_{cl}(x, t)$	Chloride Concentration at Depth with Time
RCPT	Rapid Chloride Permeability Test
RH	Relative Humidity
SCM	Supplementary Cementitious Material
T	Temperature

w/c	Water to Cement Ratio
BFS	Blast Furans Slage
SRPC	Sulfute Resestance Poratland Cement
CC	Climate Change
ppm	Part Per Million
FEM	Finite Element Method
D_{cl^-}	Diffusion Coefficient of Chloride Ions
SF	Silica Fume
FA	Fly Ash
SG	Blast Furnaces Slag
GGBS	Ground Granulated Blast Furnace Slag
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OPC	Ordinary Portland Cement
$C_{cl}(x, t)$	Chloride Concentration at Depth with Time
RCPT	Rapid Chloride Permeability Test
RH	Relative Humidity
SCM	Supplementary Cementitious Material
T	Temperature
w/c	Water to Cement Ratio
BFS	Blast Furans Slage
SRPC	Sulfute Resestance Poratland Cement
CC	Climate Change
ppm	Part Per Million
FEM	Finite Element Method

CHAPTER ONE

INTRODUCTION

CHAPTER ONE INTRODUCTION

1-1 General Overview

Chloride-induced corrosion of concrete reinforcement is still a major concern when it comes to the long-term durability and service life of reinforced concrete structures. One of the most essential aspects of the durability design of reinforced concrete structures exposed to chloride environments is the prediction of chloride ingress in concrete (Tang,2013). Concrete is a porous material with water partially filling the pores. Chloride ions migrate into concrete when it exposes to saline solutions, altering the environment around the reinforcement and causing reinforcement degradation over time (Basheer *et al.*,1996). The chloride ions travel through the concrete pore system and micro cracks and de-passivate the oxide film that protects the reinforcing steel bar that accelerates the corrosion reaction (Mehta,1997).

One of the most risks to reinforced concrete structures is chloride attack as well as carbonation (AL-Ameeri *et al.*,2021). Chloride ions may penetrate concrete from a variety of sources, including (seawater, de-icing salt, and groundwater). Internal sources include contamination in the concrete mix, such as aggregate or brackish water, as well as chemical admixtures with chloride concentration. (Neville, 2011; Dyer, 2014)

Several approaches can be employed to investigate chloride penetration in concrete, including (salt ponding test, bulk diffusion test (Nord Test ,NT Build 443), rapid migration test, electrical migration techniques and Rapid chloride permeability Test) (Stanish *et al.*,1997)

The proposed model in this research takes into account the effects of temperature, relative humidity, and crack width all at once, and it is supported by previous research. It was used to forecast chloride concentration in structures that were expected to be built in 2020 with the Intergovernmental Panel on Climate Change's climate change scenario (IPCC, 2014).

1-2 Research Importance

Climate change and other severe atmospheric conditions have a longer-term impact on the environment, by accelerating concrete deterioration and thus reducing the safety, serviceability, and resistance of reinforced concrete structures, as a result, the predicted service life will be reduced. Thus, the demand for deteriorating structural maintenance is growing at a rapid rate. To maintain infrastructure and treat problems as soon as possible before structures approach the stage of propagation, it is essential to estimate chloride penetration into reinforced concrete structures.

1-3 The Research Goals

The goal of this study is to propose the chloride concentration profile in reinforced concrete structures that take into account the effect of environmental condition such as crack width, relative humidity and temperature, supplementary cementitious materials as well as climate change impact

- 1- Proposing an integral model for forecasting the chloride concentration with depth in concrete structures.
- 2- Based on the experimental data of several researchers, a comparison was done to verify whether the model that used to provide consistent results or not.

1-4 Layout of the Research

In this study, five chapters were reviewed, which listed as following:

Chapter One (Introduction): A general overview of penetration of chloride in concrete structures, the factors that influence chloride penetration, the method for measuring penetration of chloride, and the study goals and importance were provided.

Chapter Two (Literature Review): This chapter, collection of scientific studies and researches on the sources of chloride penetration, the mechanisms of chloride penetration, the external and internal factors that influence penetration, methods of measuring chloride penetration in concrete, and the climate change scenarios of IPCC,2014 were reviewed.

Chapter Three (Methodology and Experimental work): It includes a framework for model formation, diffusion coefficient reference, and parameters (T, RH, CW), surface concentration, COMSOL Multiphysics interface for cracked and non-cracked sample, flow chart for steps using COMSOL Multiphysics to show chloride profile, climate change impact, as well as the model's application to past studies and the building's construction in 2020.

Chapter Four (Modeling and simulation of chloride penetration): It provides the results of earlier investigations that were utilized to verify the suggested chloride penetration model. The purpose of this simulation was to determine the influence of The impact of climatic change on the long-term durability of concrete infrastructure, specifically chloride penetration in concrete structures.

Chapter Five (Conclusion): In this part of study, the research's findings and suggestions, as well as the possibilities of doing more research were summarized.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO

LITERATURE REVIEW

2-1 Introduction

Some literatures related to the research topic, the source of chloride penetration into reinforced concrete structures (RCS) such as marine environment, de-icing salts, and groundwater are presented. Also, the mechanisms of chloride ingress into concrete, the factors that influence chloride penetration into concrete, external and internal factors are reviewed. Some methods for measuring the penetration and effect of the climate change on chloride penetration and concentration are investigated.

2-2 Sources of Chloride Salt's Attack Reinforced Concrete

Generally, there are three sources of chloride that attack reinforced concrete structures (Ahmed *et al.*, 2020). When it contacts with reinforced concrete, the content of chloride ions in concrete increases, consequently reduce the life service of reinforced concrete structures (Wang *et al.*, 2010):

2-2-1 Sea Water Attack (Marine Environment)

A great number of concrete structures have recently been built near, in, or beneath seawater (Mark, 2016). These structures such as a bridge, a high-rise building, or an oil platform as evidenced in Figure (2-1), are suffering protection issues due to defects of reinforced concrete especially corrosion, because seawater involves high content of chloride ions (Shen *et al.*, 2019). It was thought that the concrete is a long-lasting material, but the

characteristics of concrete can be influenced over time by the natural conditions, such as corrosion, exposure to chemicals and other forceful operations. Caused by a lack of protection, the structures approach the end of service life (Byung *et al.*, 2002). The infiltration of water, chloride, and other forceful ions into concrete is an important element in physical and chemical deterioration processes (Mehta *et al.*, 1993).



(a)

(b)

Figure (2-1): Coastal RC structures (a) Hong Kong-Macao bridge (Chine plus,2019), (b) Wharf structure <https://theconstructor.org/structures/types-marine-structures-construction-uses/16854/> .

A Particularly, important source of chloride ions in seawater in contact with concrete, marine reinforced concrete structures can be classified

into three exposure zones, submerged, dry wet cycling zone(tidal/splash), and atmospheric, are presented in Figure (2-2). The most vulnerable case is the tidal zone as a result of increase in chloride ion level as a result of exposure cycles to drying and wetting resulting in a concentration gradient in concrete (Neville, 2011).

The major ionic components of seawater are included in the Table (2-1). Among them are high levels of chloride (Cl^-) (Chang, 2008).

Table (2-1): Major ionic components of sea water (Change, 2008)

Ion	Grams per 1000 g seawater	Mass %
Cl^-	19	1.9
Na^+	10.7	1.07
SO_4^{2-}	2.7	0.27
Mg^{+2}	1.3	0.13
Ca^{+2}	0.4	0.04
K^+	0.4	0.04

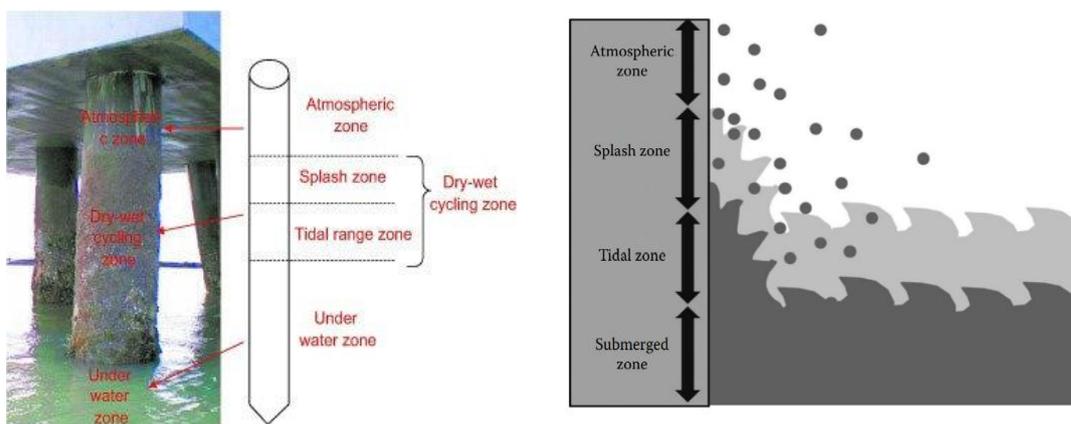


Figure (2-2): Exposure zones of concrete subjected to sea water (yujue et al., 2019)

2-2-2 De-icing Salts

In Sweden, the snow and limited temperature of ice all year leads result to commonly employed de-icing salts, to defrost the ice from the road (Tang *et al.*, 2021). As show in Figure (2-3) ,reinforced concrete structures (RCS) expose to a splash of de-icing salt on both sides of the road bridges leads to a drop the durability of these structures with the time due to increase the concentration of chloride ions (Shi *et al.*, 2012).



Figure (2-3): Exposed site for de-icing salt road environment (Tang, 2021)

Sodium or calcium chloride are the major ingredients in de-icing salts (or mixtures). The climate determines the amount and duration of implementation. Winter in the Netherlands is relatively moderate, with just a few episodes of subzero temperatures and snowfall. The typical quantity of salt spread over bridge surfaces is around 250g of chloride per square meter each year, according to estimates. This creates a aggressive environment for reinforced concrete, although the amount of salt used in many other nations is significantly higher (Polder *et al.*,2000).

According to Filanda (2008), these salts are used to facilitate easy traffic movement and keep safety during the winter. The Finnish Transport Infrastructure Agency (FTIA) used 80000-100000 tons of NaCl per year with amounts per road kilometer ranging from 2 tons/km up to 20 tons/km.

2-2-3 Ground Water

Across most places around the world especially in Iraq, ground water represents an important problem to the concrete foundations of buildings such as settlements and corrosion of reinforcement ...etc. The ground water in the middle and southern Iraq contains a great content of salts, sulfates and chloride ions in contact with concrete (Tawfek, 2017), therefore this case is also considered another source of chloride ion.

The use of de-icing salt may cause an increase in the chloride concentration of soil and groundwater. In collaboration with the final environmental management, the finish Transport Infrastructure Agency (FTIA) is measuring the chloride concentration of groundwater in general. In 49 % of the remark locations the chloride concentration tendency is increasing or heavily increasing. As in reference samples the chloride concentration in discrete groundwater sources ranged from 0.4 to 700 mg/L. The chloride concentration in classic finished groundwater is less than 0.25 mg/l. (Lindroos et al., 2015).

2-3 Mechanisms of Chloride Penetration in Concrete

The flow of liquids, ions, and gases through concrete is significant due to their interaction of hardened concrete or water content, and this can affect the honesty of concrete both direct and indirect, causing concrete structures deteriorated according to (Basheer et al., 2001). These movements are commonly referred to as penetration, and they occur as a result of varying configurations of air and water force variability, moisture variability, and solution content or temperature changes (Nilsson et al., 1996), based upon the driving factor of procedures for detrimental compounds via concrete (diffusion, absorption and permeation). The parameters have described in the next sections.

2-3-1 Diffusion

Diffusion is defined as the movement of material from one part of component of the system towards another as a result of a concentration gradient (Basheer *et al.*, 2001). Flux is a measurement unit for diffusion, and it is the density travels percentage per unit area. Fick was the first to design a diffusion-based expression in 1855 (Riyadh, 2018). The steady state is represented by Fick's first law which states that percentage of mass transfer across a section's unit area, J , is related to the content slope, $\frac{\partial c}{\partial x}$, and D is the rate of change of diffusion (Crank, 1956):

$$J = -D \frac{\partial c}{\partial x} \quad (2-1)$$

While Fick's second law can be utilized to explain the differences in a unit of volume to period through non-steady nation situations, where the content c just at the point x varies over time, t into a one-dimensional flow (Crank, 1956):

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial c}{\partial x} \right) \quad (2-2)$$

According to Verbeck (1987), the chemical interactions between penetrating compounds and concrete, are a factor to be considered when interacting with the process of diffusion. At the moisture level, for instance the spread of chloride ions into the concrete is preceded by interactions like physical or chemical adhesion, during the mixing process, chloride ions are linked through their interaction with the C3A compound, forming a compound called calcium chloroaluminate, referred to as Friedel's salts,

which are responsible for binding the free ions. as shown in Figure (2-4). A process reduces the concentration of moveable chloride ions at any given location, reducing the possibility of inward diffusion .

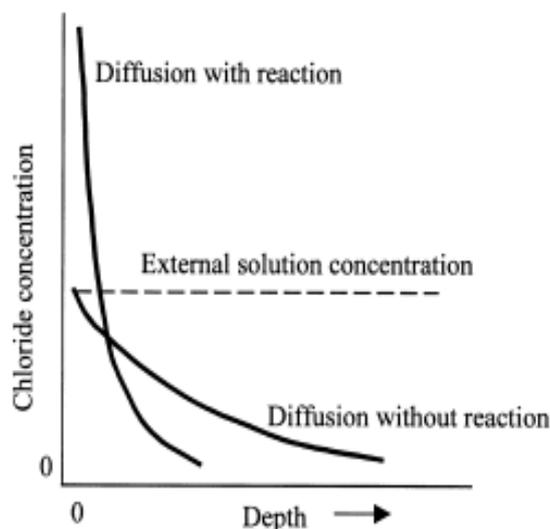


Figure (2-4): Diffusion in the presence and absence of a chemical reaction
(Verbeck, 1987)

2-3-2 Absorption

Water absorption is the movement of liquids through porous substances attributable to surface tension in capillaries. It has to do with the concrete's pore structure and moisture content (Glanville, 1931; Rose, 1965). The absorption of water in dry concrete depends on two factors:

1. The quantity of water required to permeate the concrete (the effective porosity)
2. The sorptivity increases as the percentage of capillary penetration increases.

Basheer (1991) discovered a similar equation for the water absorption action has:

$$A = C + S\sqrt{t} \quad (2-3)$$

where: A is a term referring to water usage, S is the sorptivity, t is time delayed, C is the first interruption observed by some scholars, and it is considered to be dependent on the surface ends.

2-3-3 Permeation

The capacity of channel to enable water to pass via it underneath the impact of pressure changes is referred to as permeability according to Darcy's law (Klinkenberg, 1941). The constant-state of flow percentage is directly related to the hydraulic gradient.

$$V = \frac{Q}{A} = -k\left(\frac{dh}{dl}\right) \quad (2-4)$$

where:

V :flow velocity

Q : flow

A :flow cross-section area

K :Permeability coefficient

$\frac{dh}{dl}$:pressure losses above a fluid flow span

Darcy's law is applicable to any liquid passing via a permeable material with viscous flow. Darcy's law is denoted by the equation:

$$V = \frac{Q}{A} = -\left(\frac{k}{\eta}\right)\left(\frac{dp}{dl}\right) \quad (2-5)$$

where: dp denotes the head losses along the fluid flow dl, η is the fluid viscosity and k is a perpetual attributed to as the porous medium's intrinsic permeability.

2-4 Factors Influence Chloride Penetration

External and internal factors affect the content of chloride ions in concrete pore solution as shown in details below:

2-4-1 External Factors

2-4-1-1 Temperature

According to [Hussain and Rasheed \(1995\)](#), the temperature exposure has a forceful effect in decreasing chloride permeability resistance, however, this raise leads to a decrease in $[\text{OH}^-]$ content in pore water. It creates an increase in the content of free chloride in pore water structure due to the decomposition of calcium chloroaluminate (Fridal salts) which is responsible for the binding of chloride by cement compound, C_3A .

2-4-1-2 Relative Humidity

The driver of chloride penetration in unsaturated concrete is two forces. The first is related to the concentration gradient of chloride, and other to the moisture gradient. ([Homan and Ababneh, 2016](#)). This research stated showed that moisture transport has significant increment the penetration. The higher moisture content in porous concrete distributed over the surface layers due to the gradient in moisture content from the surface to inner layers ([Meira, 2004; Bazant, 1994](#)). The wetting and drying cycles are effectively in the transfer of chloride salts via capillary action and diffusion processes ([Martin, 1999; Bamforth, 1999](#)).

2-4-1-4 Carbonation

The term "carbonation" refers to the chemical interaction between carbonic acid (H_2CO_3) (which results from the carbon dioxide reaction (CO_2) from the atmospheric, reacts with water in pore solution) and cement

hydration product such as $Ca(OH)_2$, to produce calcium carbonate ($CaCO_3$) (Papadakis *et al.*, 1992; AL-Ameeri *et al.*, 2018; Neville, 2011).

Carbonation causes changes in a mineral composition of concrete and reduce the pH of the pore solution in the matrix. Furthermore, it causes releases the bound of chloride ions which leads to increase the chloride ions content, then increase the chloride penetration into concrete is greater. (AL-Ameeri *et al.*, 2021; Wan *et al.*, 2013; Broomfield, 2007)

2-4-2 Internal Factors

2-4-2-1 Properties of Concrete

It is well established that an important feature, such as permeability influences the durability of concrete. The reduction in durability causes concrete deterioration due to factors such as the chloride penetration, carbonation, freezing and thawing, alkali aggregate reaction, etc. (Mohammed *et al.*, 1994). The permeability of cement past dependent on two parameters w/c proportion and water content, it is lower faster as w/c ratio decreases (vice versa), especially below 0.6 when the capillaries become segmented (Neville, 2011) as shown in Figure (2-5).

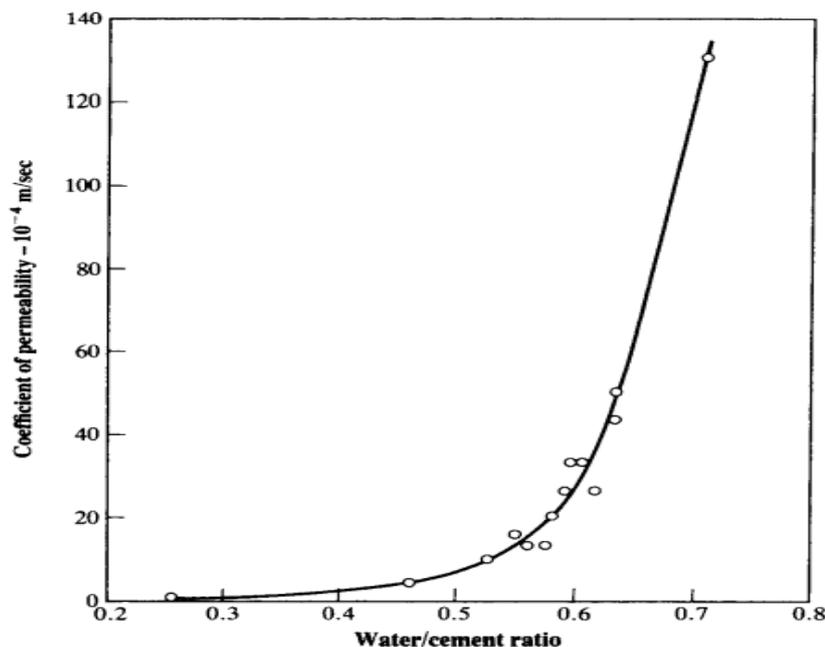


Figure (2-5): The relationship between permeability and w/c ratio in mature cement paste (Mann, 1954)

The uses of supplementary cementitious material or pozzolans such as granulated blast furnace slag (BFS),(GBS),(FA),(SF) by replacing part of cement with the mineral admixture is one important way to secure concrete from chloride ions ingress and increase the operating life of structures (Mark, 2014).

The porosity of concrete influences its transport properties. The type of binder, w/c ratio and the path of transfer for chloride in concrete. Higher w/c ratios a decrease the concrete quality due to of increased porosity and water absorption, a drooping in strength, then chloride penetration is affected (AL-Ameeri *et al.*, 2021).

2-4-2-2 Cracks

The presence of crack in reinforced concrete structures makes the concrete more likely to penetrate salts and aggressive material that accelerate the deterioration of concrete (Hailong *et al.*, 2012).

The behavior of permeation and diffusion of chloride ions in concrete with or without crack was investigated by many researchers, the length, width of crack and surface concentration of chloride show up significant impact on the penetration of chloride in crack and structure (Jin *et al.*, 2010).

2-5 Test Methods of Chloride Penetration in Concrete

2-5-1 Salt Ponding Test: (AASHTO T259) Standard Test Method of Concrete resistance to Chloride Ion Penetration

AASHTO- T259 is the first examination that covers this test. It is a long-term test for measuring the penetration of chloride into concrete.

The concrete model is enclosed all edges in this test and the 3% NaCl option is placed above the external of the concrete specimen with dimensions (300mm*300mm*75 mm) as shown in Figure (2-6).

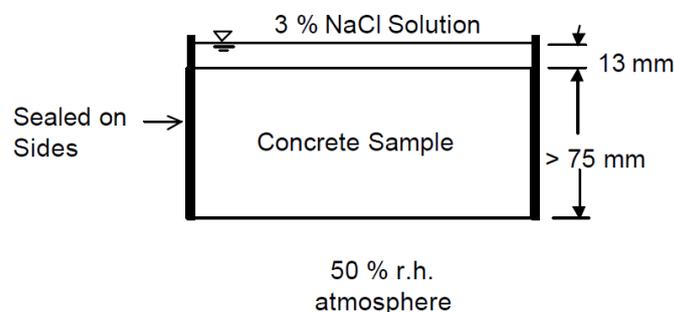


Figure (2-6): AASHTO -T259 (salt ponding) experiment (stanish *et al.*, 1997)

The following is a summary of the salt ponding test procedure:

1. When compared to the other tests. This one necessitates a good sample of concrete. Before conducting the test, three concrete slabs of length and width 300mmx300mm and thickness of 75mm are set

and treated for 14 *days* before kept for 28 days in the drying room in a 50 % relative humidity climate.

2. Every concrete slab is enclosed on both sides and for 90 days, a 3% NaCl solution is placed on the upper surface.
3. The concrete slab's bottom face is left exposed to a curing climate.
4. For 90 days, the samples are kept in a fixed value of chloride option at upper surface.

After 90 days, the sample is divided into layers with thickness of 12mm each, resulting in 6 parts for each sample.

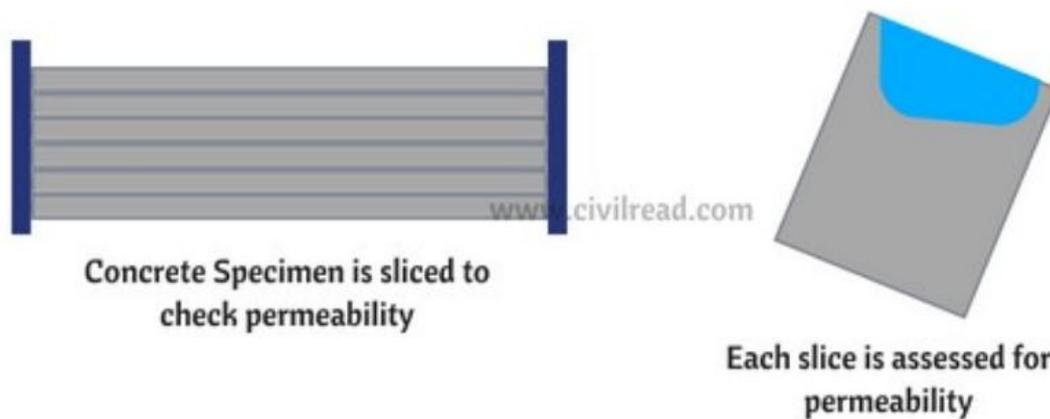


Figure (2-7): AASHTO-T259 (salt ponding) test setup after completion of 90 days (stanish et al.,1997).

If the concrete is impermeable, the chloride permeation in the layers is zero. If the concrete is permeable, chlorides can permeate up to a second and third layer from the upper layer.

2-5-2 Bulk Diffusion Test (Nord Test NTBuild 443)

To recognize some of the lacks of the salt ponding test for measuring diffusion, a bulk diffusion test was created. The Nord test is first officially provided diversity of the bulk diffusion test, despite not being the primary similar check created. The initial moisture condition of the sample is the

first difference in the test procedure from the salt ponding test. The test specimen is saturated with limewater rather than after 28 days of drying as in the salt ponding test. When chloride solution is created, This eliminates any early sorption effects. Furthermore, rather than coating only the sections of the specimen and leaving one exposed to air, the only side exposed to a 2.8M *NaCl* solution is left uncovered as show in Figure(2-8). Before being reviewed, it is left in this state for at least 35 days [Nord Test, NT Build 443-94].

The chloride characteristic of the concrete is calculated by mounting The specimen by using a diamond-tipped bit to assess the specimen. The model is levelled in order for the bit's axis of advancement is perpendicular to the sample's surface. A throw is complete at every deep to squeeze the dusting a concrete sample, which is then obtained. This is replicated at increasing depths, with depth increments of about 0.5 mm. The powder's chloride content is then calculated using AASHTO-T260. The curve is then fitted with the error function solution of Fick's Second Law, and a diffusion valuation and surface chloride content are calculated.

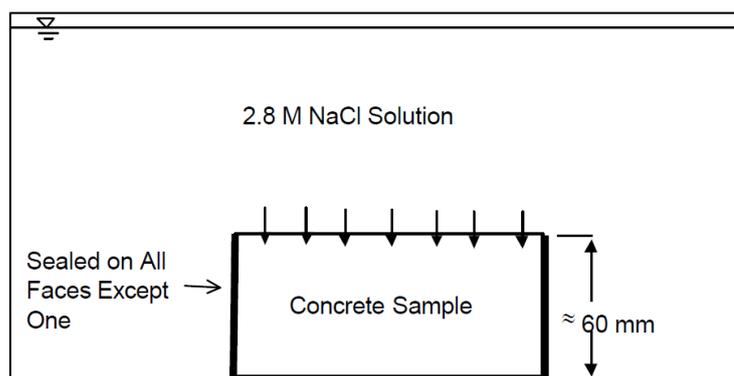


Figure (2-8): Nordtest test (stanish et al.,1997).

2-5-3 AASHTO T277: Rapid Chloride Permeability Test

AASHTO T 277 covers the Rapid Chloride Permeability test for ions of chloride. This assessment is used to determine the concrete's resistance to penetration of chloride ion.

This test shows how well concrete can resist chloride ion penetration using electricity. The service life of concrete structures can be predicted using this test. It can also be used for quality control based on durability. The continuous voltage (V) is implemented to 6 hours on a concrete specimen in this test, and the current is measured. The coulombs are calculated by measuring the flow (I) via the concrete. Amperes are used to measure current. A coulomb is equal to one ampere per second, so one coulomb equals one ampere passed through the concrete specimen in one second, and 60 coulombs equals the charge passed in 60 seconds. The greater coulombs, more permeable concrete; the lower the coulombs, less porous the concrete. This test is prepared possible using Rapid chloride permeability test equipment.

Two reservoirs make up the test tools. One reservoir contains 3% $NaCl$ solution, while other contains 0.3M $NaOH$ solution. A concrete specimen with a thickness of 50mm and a diameter of 90-100mm can be used as a test sample, as see in Figure (2-9).

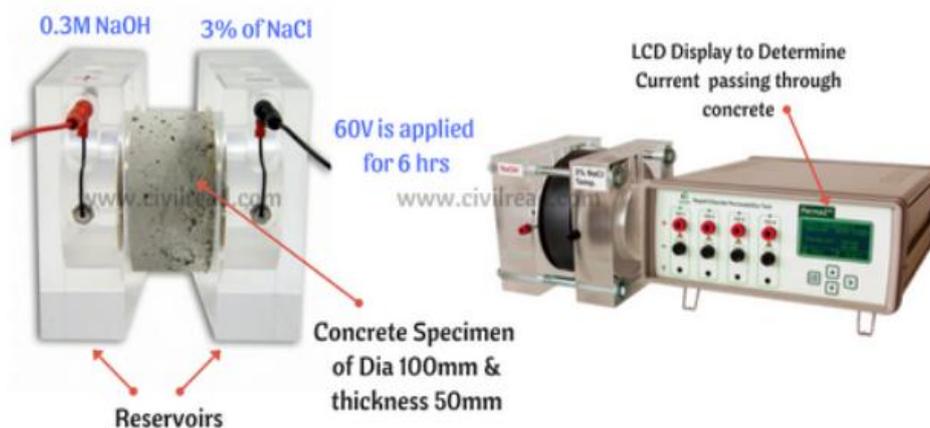


Figure (2-9): RCPT test apparatus (krishna,2018)

Chloride test procedure is:

1. A concrete cylindrical specimen with a diameter of 100mm and thickness of 50mm is set and submerged.
2. The specimen of concrete is put among two reservoirs layers (referred to as an individual cell) in which one contains a NaCl solution and the other a NaOH solution.
3. The Dc power source is being used to power these reservoir layers, and a 60V voltage is applied to both sides of the concrete samples for 6 hours.
4. Now, measure the current traveling through the concrete at various time intervals.
5. The current passing through the concrete is determined by an LCD linked to the cell.

To calculate the concrete permeability, 2-3 samples of the same concrete mix are taken and tested as directed, with the average value utilized as the final result. Permeameters can also include up to three cells, each with its own LCD digital meter for analyzing up to three samples at once. Table (2-2) can be used to evaluate concrete quality.

Table (2-2): RCPT evaluations (per ASTM C1202)

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
< 100	Negligible

2-5-4 Electrical Migration Techniques

A lower intensity electrical field than used in the *RCPT* is typically used to promote chloride transport. Data can also be collected in a different fashion in order to provide a more accurate appraisal of the situation.

Electrical migration experiments are carried out in a two-chamber cell, with chloride ions present in the cathode chamber but not in the anode chamber, and the concrete sample dividing the two chambers, as shown in Figure (2-10). A disc with diameter of 100mm and a length of 15 to 50mm is used as a concrete sample. The disc thickness will affect the test time, but a large enough size is required to prevent aggregate interface affects.

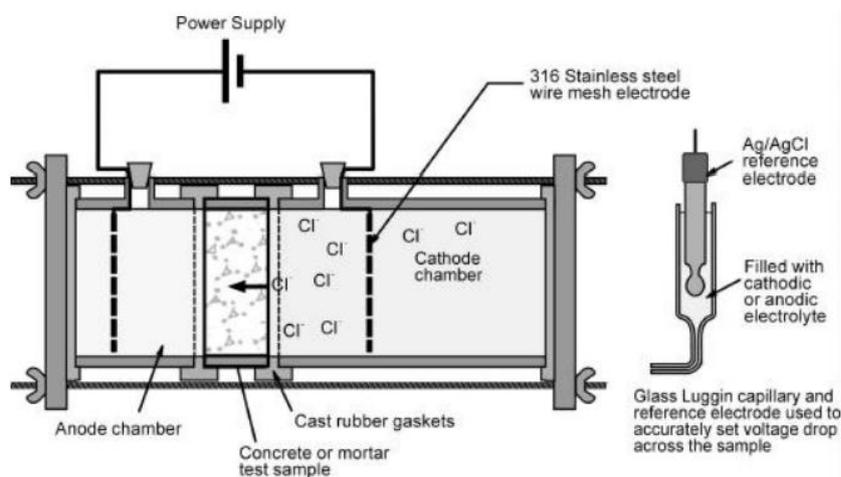


Figure (2-10): Typical chloride migration cell (stanish et al.,1997).

The sample thickness must really be bigger than the maximum particle size to avoid a faster pathway for chloride ions to flow through. This is owing to the likelihood of a weak transition zone surrounding the aggregate that extends most of the way through the sample.

The chloride ions are then forced via concrete with a voltage whereas the downstream chloride content (anode chamber) solution is measured, which is commonly done by isolating microscopic aqua lots and on a regular basis, the chloride concentration of these samples is measured. The change in chloride content over time can be used to calculate diffusion coefficients.

The voltage that is applied is the most evident and significant variation that might develop between different testing procedures. This has a direct impact on the amount of time it takes to complete the test. It's important to use a voltage that's lower enough to reduce heat the sample but higher enough to ensure a short test duration. In most cases, the voltage range is 10 – 12V (Alexander *et al.*, 1995; Zhang *et al.*, 1991).

In an electrical migration cell, the many shortcomings of the AASHTO T277 test can be remedied not by changing the assessment equipment or parameters in respect to the *RCPT*, but by modifying how the assessment is evaluated. To ensure that the diffusion coefficient, D , is determined purely using chloride ion movement, the chloride ion level in the downstream solution must be measured on a regular basis. The downstream chloride ion contents are then shown as a function of time, providing a curve that resembles Figure (2-11), with a low initial chloride content due to background chlorides in the concrete.

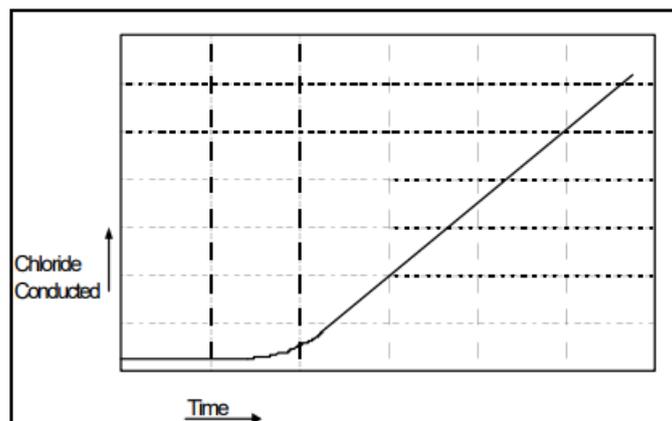


Figure (2-11): A typical plot of migration (downstream chloride content versus time) (stanish et al.,1997).

2-5-5 Rapid Migration Test (CTH Test)

The classic migrating cell was modified by Tang and Nilsson (1991). A migration cell with a sample 50mm in thickness and 100mm diameter, as well as a 30 V applied voltage, is shown in Figure (2-12).

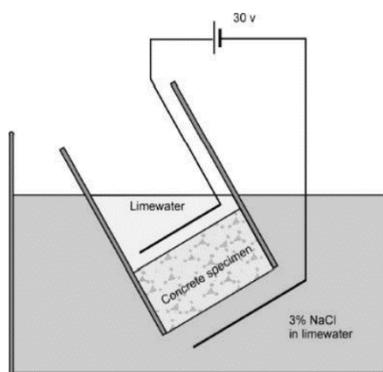


Figure (2-12): Migration cell of Tang and Nilsson (stanish et al.,1997).

The electrical migration experiment continues normally, with the exception that the chloride content in the downstream solution is not detected. Alternatively, after a set amount of time (8 hours were used by Tang and Nilsson). According to the specification (NT BUILD 492), the samples are removed and separated, and the thickness of chloride ingress in one part of the sample is assessed using a colorimetric method based on a

silver nitrate solution. A chemical reaction happens when a silver nitrate solution is sprayed over concrete that contains chloride ions. Silver chloride, a white material, is formed when the chlorides attach to the silver. The silver in the concrete binds with the hydroxides rather than the chlorides, giving it a brownish hue.

The chloride ion diffusion coefficient can be calculated using the depth of penetration. Using the following equation (Tang and Nilsson, 1991), which is derived from the Nernst-Einstein equation:

$$D = \frac{RT}{zFE} * \frac{x_f}{t} \quad (2-6)$$

where x_f signifies the chloride ion profiles' inflection point, which must be linked to the colorimetric thickness. The penetration depth may be a useful metric on its own. $E(x)$ is the applied electrical potential as a function of x , z is the valence of ionic species, and F is Faraday's constant. R is the universal gas constant; T is the temperature.

In terms of examining actual chloride ion movement and temperature increase, the *CTH* test, like the more frequent migration cell, can overcome the *RCPT*'s drawbacks. When conductive resources, such as metals or Carbon, are added to *CTH* Cell, the current is supplied by the conductors instead of the ions in the solution for pores, as in a typical migration test. If the conductors do not short-circuit the cells (for example, if a piece of steel is parallel to the plane), the chloride ions may react with it, disrupting ion flow. This would not be a problem if the chloride ions did not penetrate the steel depth.

2-6 Summary the Test Techniques

The test procedures covered in the preceding sections are summarized in Table 2-3, which is divided into three groups (long term, short term, and other). This table summarizes several of the advantages and disadvantages of every test procedure.

Table (2-3): Summarizes the test techniques

Test Method	Considers Chloride Ion Movement	At a Constant Temperature	Unaffected by Conductors in the Concrete	Approximate Duration of Test Procedure	
Long Term	AASHTO T259 (salt ponding)	Yes	Yes	Yes	90 days after curing and conditioning
	Bulk Diffusion (Nord test)	Yes	Yes	Yes	40 - 120 days after curing and conditioning
Short Term	RCPT (T277)	No	No	No	6 hours
	Electrical Migration Rapid Migration (CTH)	Yes	Yes	No	Depends on Voltage and Concrete

2-7 Impact of Climate Change on Chloride Penetration

The International Panel on climate change (*IPCC,2014*) examined several climate scenarios, which were split into four categories: *RCP2.6*, *RCP4.5*,

RCP6.0, and *RCP8.5*, which included variations in the atmosphere, ice, oceans, and sea level rise.

Carbon dioxide (CO_2) emissions from human activities such as fossil fuel combustion, cement manufacture, hot springs, and volcanoes increased the greenhouse gases in the atmosphere from 1850 to > 2000 years, as shown in figure (2-13).

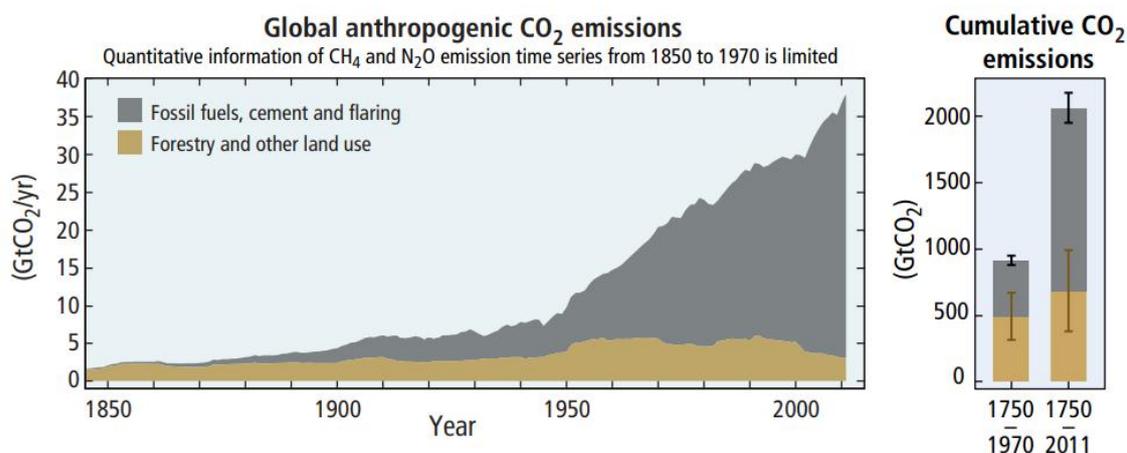


Figure (2-13): Carbon dioxide (CO_2) emission (IPCC,2014)

Overall, anthropogenic global warming increased from 1970 to 2010, with annually absolute rising from 2000 to 2010 of around 49 ± 4.5 GTCO₂ equivalent in 2010, and carbon dioxide emissions from fuel combustion have reached their highest level ever had with 78 % of the rise in greenhouse gas emissions due to fossil fuels and industrial operations (1970-2010).

As illustrated in Figure (2-14), the IPCC's Assessment Report 5 (2014, AR-5) proposes four representative concentration pathways, for carbon dioxide (CO_2) emissions and temperature: *RCP 2.6*, *RCP 4.5*, *RCP6.0* and *RCP 8.5*.

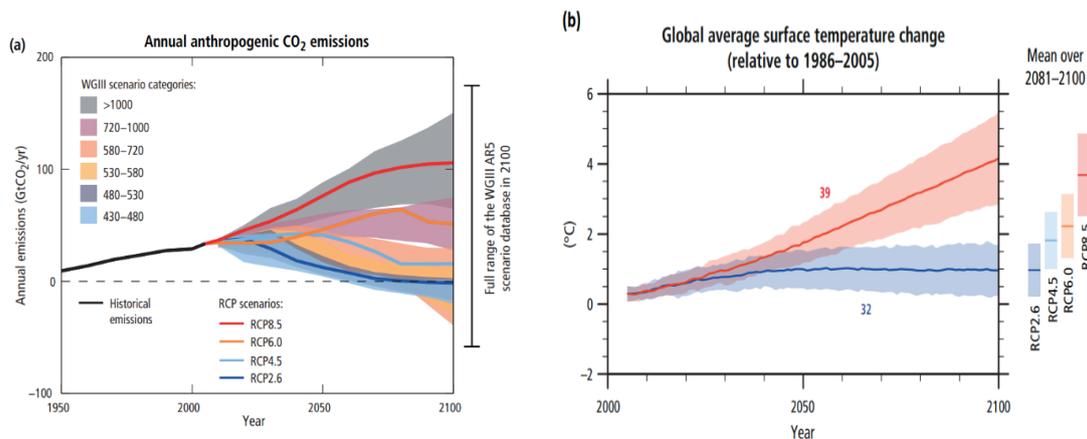


Figure (2-14): Show (A) annual CO_2 emissions and (B) change in average global surface temperature from 1986-2005. (IPCC, 2014)

Figure(2-14a) left focuses on CO_2 emission, the IPCC's worst-case scenario, *RCP 8.5*, has CO_2 emissions exceeding 1000 parts per million. The temperature expected to change at the end of the 21st (2081-2100) it expected to excess 1.5°C for *RCP 4.5*, *RCP6.0*, *RCP 8.5* and it most probably excess 2 C for *RCP 6.0*, *RCP8.5* as shown in Figure (2-2b) (IPCC, 2014).

When a result of climate change, chloride penetration in *RC* structures will rise as rise CO_2 emissions, temperature, and dropp in relative humidity decrease (IPCC, 2014).

2-8 Concluding Remarks

This section of the chapter provides an overview of chloride penetration in concrete, beginning with the sources of chloride, which are represented by over exposure from different sources, external sources (seawater, de-icing salt, and groundwater), and internal sources include contamination in the mix of concrete, aggregate or brackish water, as well as chemical admixtures containing chloride, as presenting bellow :

1. Using coupled transport techniques such as diffusion, permeation, and capillary sorption, the flow of chloride through pores is generated by a combination of the concentration gradient of chloride ions, the pressure gradient, and capillary sorption.
2. Clarification of the external factors that encourage penetration, (the temperature as increase lead to dissociation of Friedel salt's which responsible for the binding of chloride by cement compound, C_3A , by increase the relative humidity, result of the gradient of moisture content from the surface to the inner layers leads to a rise in the concentration of chloride. Carbonation of concrete engorges the penetration of concrete, to clarify the impact of internal factors represented by water-cement ratio leads to increase the porosity of concrete it causes penetrate the chloride, as increase the width crack the diffusion of chloride increase and the effect of supplementray cementitious materials.
3. Discussion Methods test chloride penetration in Concrete, categorizing them into three groups (long term, short term, and other)
4. According to IPCC,2014 studied several climate scenarios divided into four scenarios *RCP2.6*, *RCP4.5*, *RCP6.0*, *RCP8.5* the temperature rich 4°C at the end of the 21st

CHAPTER THREE

METHODOLOG AND EXPERIMENTAL WORK

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3-1 Introduction

The major purpose of this research is to predict theoretical model for chloride penetration in reinforced concrete structures when the RC_S is exposed to a different source of chloride, such as seawater, de-icing salts, or groundwater. Temperature, relative humidity, crack depth and the impact of climate change are all factored into the suggested model.

The framework for the proposed model in this study will be described in this chapter. The diffusion coefficient (D_a) and surface concentration (C_s) of the chloride ion in RCs are the most important parameters in this framework. The influences of numerous parameters are taken into account in Da (temperature, relative humidity, and crack width). Previous studies were used to validate the suggested modelling so that it could be used to forecast future chloride concentration in RC owing to climate change.

3-2 Framework For Proposed Model

The requirements of the second Fick law are used to create a model for simulating chloride penetration in reinforced concrete structures because chloride ion diffusion is non-steady-state and chloride concentration in solution that contact with RC_S changes with time that leads to the variable of Cl ions concentration over time (Basheer *et al.*, 2001). The proposed

approach for accounting for chloride penetration in reinforced concrete structures is depicted as a flowchart in Figure (3-1). Where the concentration of C_{cl-} changes over the time at point x (Basheer *et al.*, 2001) as shown in Equation (3-1).

$$\frac{\partial}{\partial t} (C_{cl-}) = D_{cl-} \frac{\partial^2}{\partial x^2} (C_{cl-}) \quad (3-1)$$

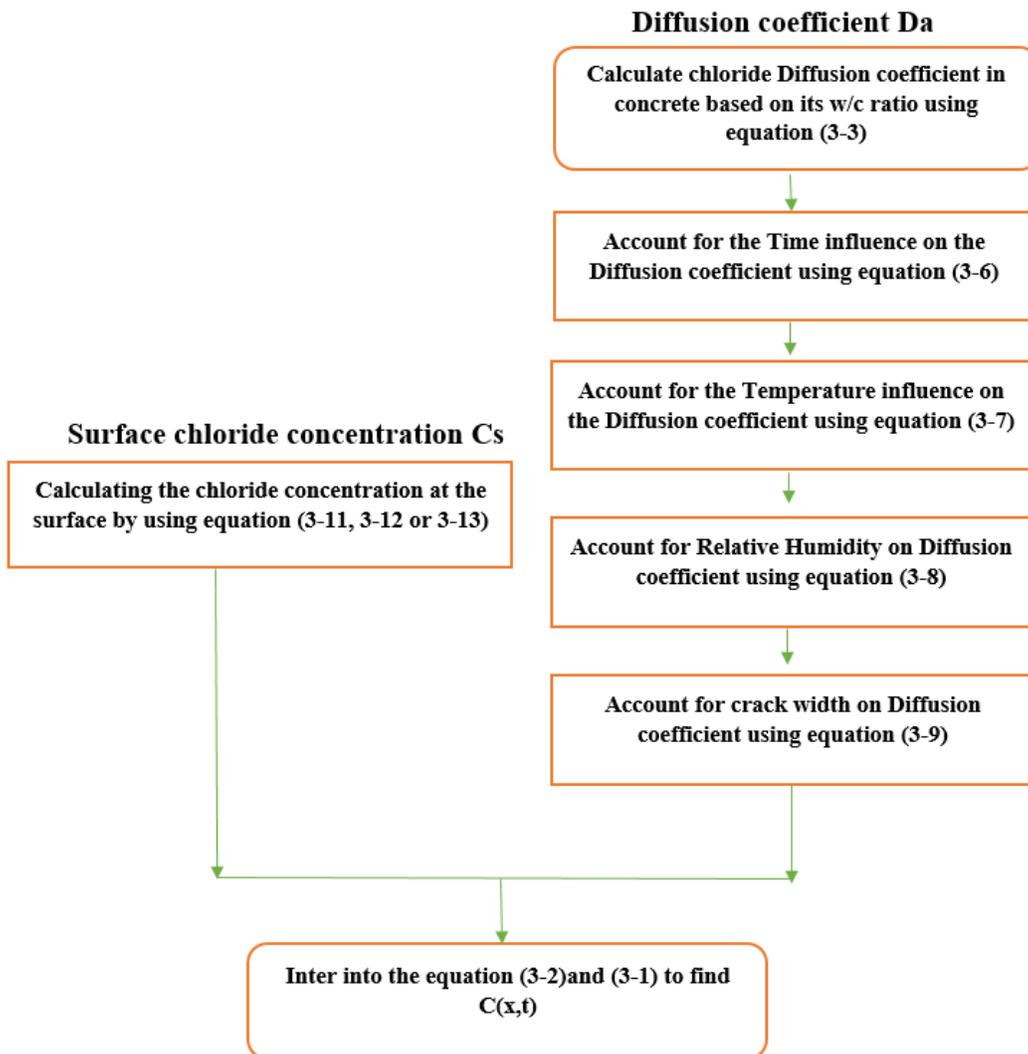


Figure (3-1): Flowchart for determining the chloride profile.

3-3 Diffusion Coefficient of Chloride Ions (D_{a,Cl^-})

Various parameters influence the diffusion coefficient of Cl^- ions in RC structures, including temperature, relative humidity, and crack width) as indicated in Equation (3-2)

$$D_a = D_{a,ref} f_{C1}(t) f_{C2}(T) f_{C3}(RH) f_{C4}(W_c) \quad (3-2)$$

where: $D_{a,ref}$ is the value of D_{a,Cl^-} for uncracked sample under reference condition of temperature and relative humidity. $f_{C1}(t)$, $f_{C2}(T)$, $f_{C3}(RH)$, $f_{C4}(W_c)$ are functions of time, temperature, relative humidity and crack width. This will be detailed in more detail in the following section.

Using the empirical equation published by (Service Life ACI 365.1, 2014), certain data pertaining to water-cement ratio and kind of cement were collected in order to determine the coefficient of chloride ions in RCs.

$$D_{a(28)} = 10^{(-12.06 + 2.4 \frac{w}{c})} \quad (3-3)$$

where w/c denotes the water to cement ratio

Service Life ACI 365.1(2014) Concrete's permeability and diffusivity are known to be significantly reduced when silica fume is added. Life-365 reduces the value established for Portland cement, OPC, by a factor based on the degree of silica fume (% SF) in the concrete. The following equation, which is also based on bulk diffusion data, is used:

$$D_{SF} = D_{PC} \cdot e^{-0.165 \cdot SF} \quad (3-4)$$

Slag from blast furnaces with fly ash Both materials have an effect on the rate of diffusion and as a result, the value of m . Use the equation below to modify the amount of fly ash (FA %) and Slag from blast furnaces (SG %) in the mixture.

$$(3-5) \quad m = 0.2 + 0.4(\%FA/50 + \%SG/70)$$

The relationship is only valid up to 50 % fly ash or 70 % slag replacement levels, and m cannot reach 0.60 (as would be the case if these maximum quantities of fly ash and slag were used), therefore m must satisfy $m \leq 0.60$ (Service Life ACI 365.1, 2014).

3-3-1 Exposure Time

The diffusion coefficient decrement in the first five years rapidly, after that the value of D_a will be constant (Bamforth et al.,1997). Dependent on the exposure period some researchers like Takewaka et al., (1988) proposed an empirical equation that designed to decrement the diffusion coefficient with an exposure time). In the literature, the following equation has been frequently suggested to account the impact time on diffusion coefficient:

$$f_{c1}(t) = \left\{ \frac{t_{ex}}{t} \right\}^m, t > t_{ex}, 0 \leq m \leq 1 \quad (3-6)$$

where: t_{ex} denotes the initial time of exposure, t denotes the time select, m denotes the diffusivity decrement factor (ageing factor), as determined by development of strength concrete, water mixture, and category of binder used in concrete (cement, FA, SF, GGBS) as well as environmental condition (Broomfield, 2007). The diffusivity decrement factor values range (0.21-0.65) (Wang et al., 2016).

CEB-FIP (2010) find the value of the ageing factor is between 0.2 and 0.8. ACI committee 365(2018) suggested the same equation (3-6) is used for a year about 25 years after that the D_{acl-} is decreased with time and $D(t)$ will be constant at Da (25 years).

3-3-2 Temperature

As mentioned in chapter two, the temperature affects diffusion coefficient of Cl^- , and to investigate that, Trapper *et al.* (2008); Thomas *et al.* (2012) used Equation (3-7):

$$f_{c2}(T) = \exp\left[\frac{U_c}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3-7)$$

where: U_c is the diffusion cavitation energy, Page *et al.* (1981) empirically calculated the activation energy for Cl^- diffusing in RC structures, taking into account water to binder ration, when it has value 0.4 it was 41.8 ± 4 (KJ/mol) , w/b is 0.5 the value is 44.6 ± 4.3 (KJ/mol), water mixture is 0.6 the value is 32.0 ± 2.4 (KJ/mol). R denotes the constant refer to gas (8.314j/mol.k), T_{ref} denotes the reference temperature (298 k) , and T denotes the temperature of interest.

3-3-3 Relative Humidity (RH)

As previously stated water content in the pores of cementitious materials has a major impact on chloride penetration, the diffusion coefficient of Cl^- ions increment as relative humidity increment. To check this out Val and Trapper (2008) have used equation to simulated relative humidity effect on chloride penetration as shown in Equation (3-8):

$$f_{c3}(h) = \left[1 + \frac{(1-h)^4}{(1-h_c)^4} \right]^{-1} \quad (3-8)$$

Where: $f_{c3}(h)$ refers to humidity, h is a percentage of humidity, h_c is the critical humidity level at which the diffusion coefficient is reduced to half its lower and upper limits ($h=0.75$) (Val *et al.*, 2008).

3-3-4 Crack Width (W_c)

As the width of crack increase the diffusion coefficient of chloride ions increase, AL-Ameeri *et al.* (2021) proposed an equation to appear the influence of crack width on the diffusion rate on chloride ions in RC structures as shown in Equation (3-9):

$$f_{c4}(W_c) = 0.934W_c^2 + 0.974W_c + 1 \quad (3-9)$$

where $f_{c4}(W_c)$ is the ratio of the chloride ion diffusion coefficient in cracks in concrete, while W_c is the crack width in concrete (mm).

3-4 Surface Concentration of Chloride Ions (C_{scl^-})

The surface concentration of chloride ions on the first layer of the sample can be determined using environmental conditions. Surface chloride concentration is assumed to be a feature of properties of concrete, such as the w/c rate (Chalee *et al.*, 2009) and hazard environment, such as ocean and deicing regions (Song *et al.*, 2008; ACI Committee 365: 2018), and exposure factors such as temperature and humidity levels. Kassir and Ghosn (2002) proposed an exterior chloride intensity framework for concrete structures exposed to deicing salt obtained from field research conducted

over 15 years on 15 bridge decks exposed to deicing salt in the snow belt region.

$$C_s = C_o(1 - e^{-\alpha t}) \quad (3-10)$$

where: α is refer an age factor of 0.25 (year⁻¹), c_o is the maximum chloride concentration (5.343 kg/m³), and t is the time measured in years.

Phurkhao and Kassir (2005) used a slope-type exterior concentration of chloride for exterior chloride on highway bridges, that is usually extracted by de-icing salt, as shown in Equations (3-11), (3-12):

$$C_s(t) = \frac{C_o}{t_o} t \quad 0 \leq t \leq t_o \quad (3-11)$$

$$C_s(t) = C_o \quad t \geq t_o \quad (3-12)$$

Song *et al.* (2008) presented a model that can predict the exterior concentration of chloride for concrete buildings subjected to the water ecosystems, trying to take time-dependence, the original build of chlorides on the concrete exterior, and the level of exposure (tidal/splash, submerged zone, and aerated zone) into account. These model's are unable to predict the concentration of chloride of concrete buildings subjected to water ecosystems either in the short or long term. The chloride concentration at an initial stage of exposure is voided in a chloride environment. To account for the original build of chlorides, the following framework is presented which was scientifically generated from reported Cs data as shown in Equation (-13 3) (**Song *et al.*, 2008**).

$$C_s(t) = C_{si} + \beta \ln(t) \quad (3-13)$$

where $C_s(t)$ denotes the chloride content on the surface at period t (%/m³), C_{si} denotes the exterior chloride (%/m³) only at the regular time (1 year or 28 days) and β is the value of a constant.

C_{si} and β are determined by environmental factors, for example, 3.0431 % and 0.685 % by weight of cement.

ACI committee 365 developed a model (service life prediction)-It was created to assist in the planning and construction of concrete buildings that would be exposed to chlorides during service. Surface chloride concentration increases with time and becomes stable at a given time, depending to the kind of exposure situation and location of the buildings (Service life 365, 2018) as illustrated in Figure (3-2):

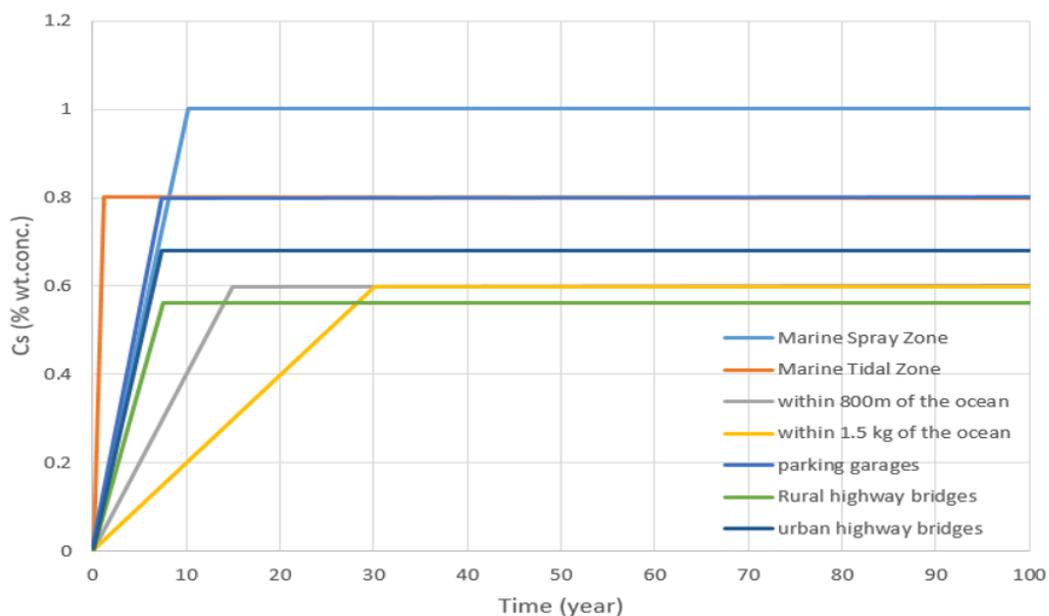


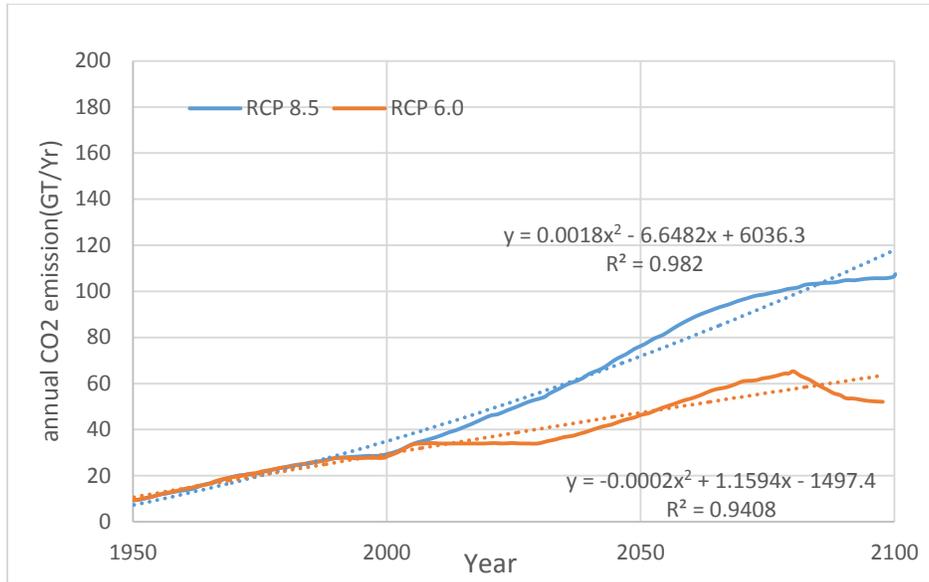
Figure (3-2): Surface chloride concentration with time (Service life-365,2018)

3-6 Model of Climate Change or Senior Climate Change

As previously stated, climatic change has a significant impact on chloride penetration in RC structures, (IPCC, 2014). It has been a change in climate over the twenty-first century, with a rise in temperature, ocean level, CO_2 emissions, and a drop in humidity levels. In this methodology take into account the worst case which is represented by *RCP 6.0* and *RCP 8.5*.

The (IPCC,2014), (AR5, RPC 8.5) investigate at the end of 21st (2081-2100), the carbon dioxide emission excess 1000 ppm and the temperature rise about $4^{\circ}C$, from this equation proposed use to prediction of temperature and carbon dioxide as shown in Figure (3-3) and their effect on chloride penetration in *RC* structures:

(a)



(b)

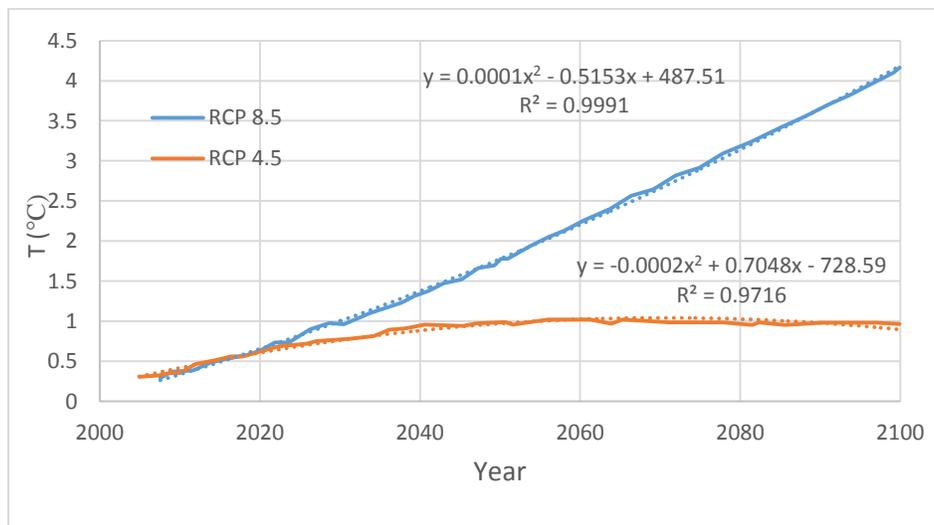


Figure (3-3): Prediction of (a) CO₂ emission. (b) increase in temperature from (2000 to 2100) (IPCC,2014, AR5)

3-7 Proposed model's Application in Predict Chloride Penetration in Reinforced Concrete Structures

3-7-1 Use the Previous Studies to Verify the Proposed Model

The proposed model was applied on previous studies and classified according to the factors affecting chloride penetration, concrete consisting of (OPC,SRPC) and concrete containing supplementary cementitious materials) (SCM), with various (water-cement ratios, temperature, relative humidity and crack width as shown in Table (3-1).

This methodology is based on a case of exposure to different chloride-containing sources, such as the marine environment and de-icing salts, as mentioned previously in the chapter two, taking into account the data in Table (3-1) and groundwater condition depending on the concentrations reached by [Tawfek, \(2017\)](#), the reference samples are cured in drinking water with a NaCl concentration of 4 mg/l (normal water), while the other samples are cured in salty water with a NaCl concentration of 4000 mg/l (a doubled value of the concentration of NaCl in ground water of Al Najaf city in Iraq)

In this study, finite element method used to solve the equation (3-1) and find the chloride concentration in RC structures ($C_{cl}(x, t)$). In this study, a commercial program, COMSOL Multiphysics (5th version) is used and employs the finite element method to find the results of problems.

CHAPTER THREE METHODOLOG AND EXPERIMENTAL WORK

Figure (3-4),(3-5) displays the steps and software application that was used to forecast chloride penetration in cracked and non-cracked reinforced concrete structures in this study.

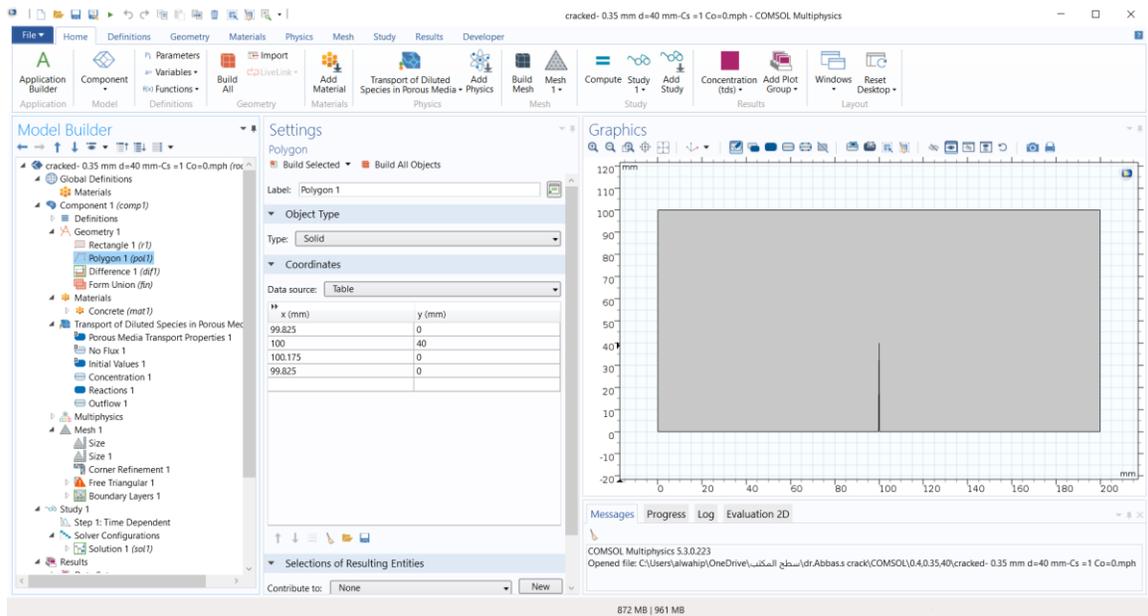
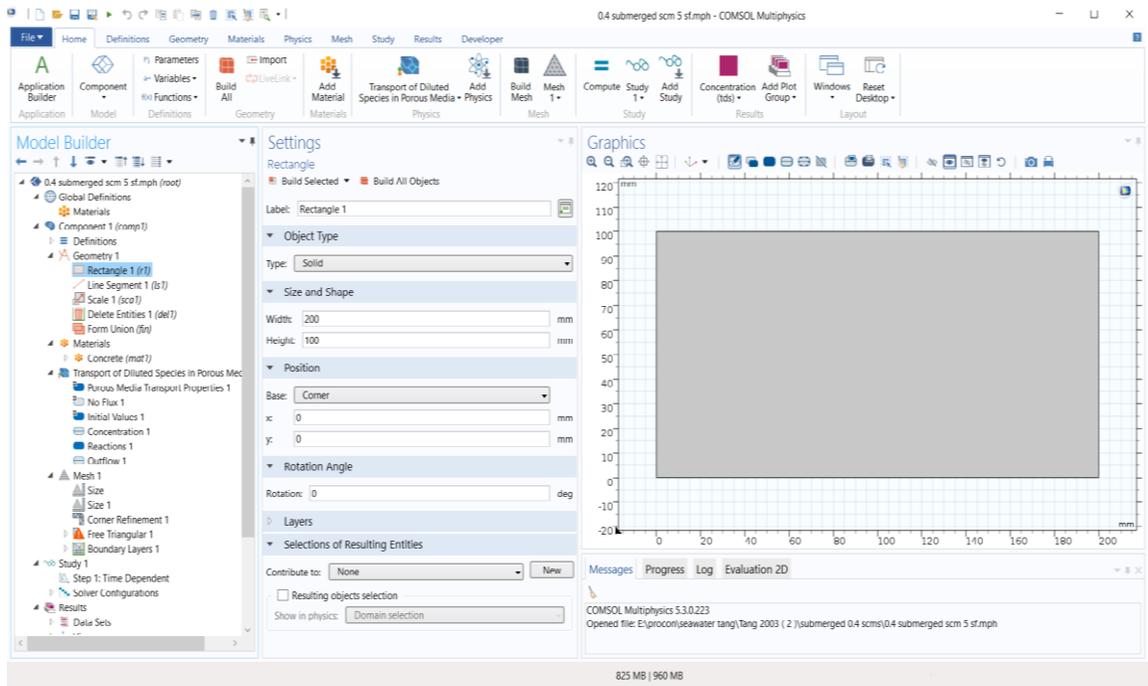
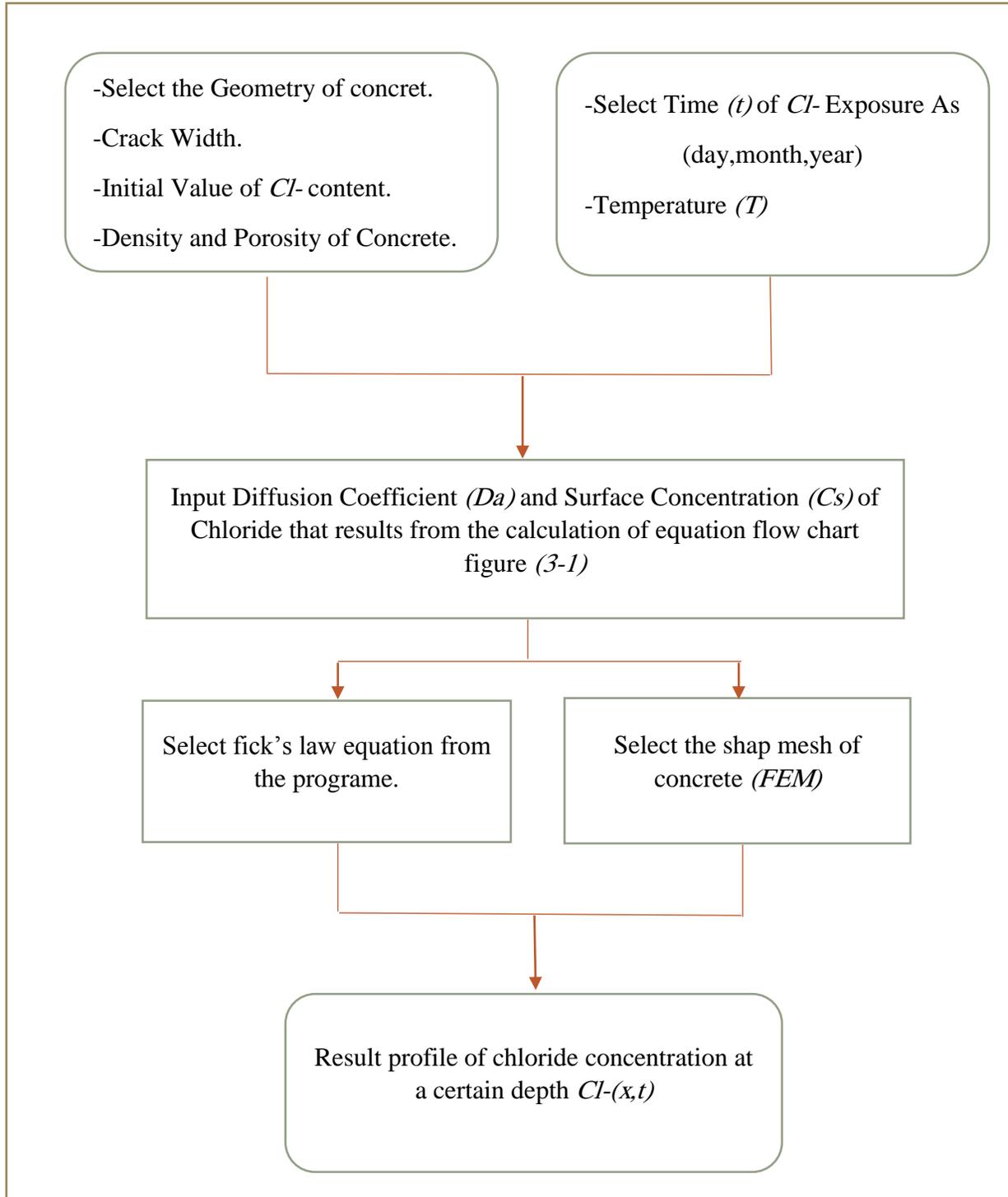


Figure (3-4): COMSOL Multiphysics interface for cracked and non-cracked sample



Fiuger (3-5): Flowchart for steps using COMSOL Multiphysics to show chloride profile.

Table (3-1): Pervious studies that used to verify the proposed model

Exposure condition	Factors	(water/binder) ratio	Cement content kg	Water content	SCMs	T °C	RH %	Crack width (mm)	Research
De-icing salts	Relative humidity Temperature	0.40 OPC 0.45 OPC 0.45 OPC	400 320 320	160 180 180	- 10 SF 20 BFS	1°C 5°C	100% 75%		Bernal et al. (2016)
Submerged Splash atmospheric	Supplementary cementitious material (SCMs)	0.4 SRPC 0.4 OPC 0.4 SRPC	420 420 420	168 168 168	- - 95%SRPC+5% SF	10□	80%		Tang (2003)
Submerged Submerged	Water/cement ratio (SCMs)	0.3 SRPC 0.35 SRPC 0.4 SRPC 0.35 OPC 0.4 OPC 0.5 OPC	492 450 420 450 420 390	147.6 157.5 168 157.5 168 195	- 95%SRPC+5% SF 95%SRPC+5% SF -	10□	80%		Tang (2003)
Tidal zone	w/c ratio crack	0.39 OPC 0.55 OPC	454 304	177 166		40°C	60%	0.2	Ishida et al.(2009)
-	w/c ratio Temperature	0.4 OPC 0.5 OPC	380 360	152 180		20,200, 600°C			Zhiming et al. (2019)
Seawater Tidal zones	Water /cement ratio SCMs	0.4 OPC 0.6 OPC	513 350	205 205		25°C	65%	0.1 0.2 0.35	AL-Ameeri et al. (2020)

3-7-2 Application on Structures Were Built in 2020

The proposed model's applicability, depending on the exposure environment, two concrete structures were assuming, the first in Basra city (Shat alarab) was built in 2020, and the second culvert structures in Najaf city.

a) Structures Exposed To Marine Environment

In marine environment the sever dangerous due to the wet and dry circle lead to high concentration of salt's that exposure to structures, to check the model proposed by the following:

1. Use the water cement ratio 0.5
2. Deep cracking action 20 mm with crack width 0.1
3. Time exposure 25 and 50 years
4. Application the scenarios of climate change **IPCC, 2014**
5. Use the model that proposed in Chapter 3 with COMSOL Multiphysics to find the results of problems.

b) Structures Exposed To Groundwater

1. Use the water cement ratio 0.4
2. Deep cracking action 20 mm with crack width 0.1
3. Time exposure 25 and 50 years
4. Application the scenarios of climate change **IPCC, 2014**
5. Use the model that proposed in Chapter 3 with COMSOL Multiphysics to find the results of problems.

CHAPTER FOUR

MODELLING RESULT AND DISCUSSION OF CHLORIDE PENETRATION

CHAPTER FOUR MODELLING RESULT AND DISCUSSION OF CHLORIDE PENETRATION

4-1 Introduction

In this chapter, the parameters that influence chloride penetration in concrete structures, as well as previous examination that were utilized to validate the chloride penetration model will be investigated and discussed. Secondly, climate change was taken into account in order to predict the extent of its impact on the propagation of chloride in concrete structures based on the chloride-containing exposure environment.

In this chapter of the current research, the chloride penetration and concentration in concrete buildings are forecasted. The numerical modeling is tested and compared to experimental data from previous studies, particularly in the area of chloride penetration. Climate change, temperature, relative humidity concentrations scenarios of (IPCC, 2014) were addressed in predict the chloride penetration in these structures.

4-2 Numerical Modelling Simulating the Chloride Penetration For Concrete Structures

Most of the models developed in simulate chloride penetration in RC structures, as described in Chapter 3, are based on the diffusion law of either the first or second of Fick's law. Because the diffusion of chloride ions concentration is a non-steady state or changeable with time due to a

changing concentration gradient with time. Fick's Second Law is used in this study as shown in Equation (4-1) (Crank, 1956).

$$\frac{\partial}{\partial t}(C_{cl-}) = D_{cl-} \frac{\partial^2}{\partial x^2}(C_{cl-}) \quad (4-1)$$

where the concentration of C_{cl-} changes over the time (t) at point x and D_{cl-} is the diffusion coefficient of chloride ions.

The proposed model of diffusion coefficient that considers the impact of time progress, temperature, relative humidity and crack width is employed Equation (4-2) in Equation (4-1).

$$D_a = D_{a,ref} f_{C1}(t) f_{C2}(T) f_{C3}(RH) f_{C4}(W_c) \quad (4-2)$$

where: $D_{a,ref}$ is the value of $D_{a,cl}$ at reference condition for temperature, relative humidity for un-cracked sample. $f_{C1}(t)$, $f_{C2}(T)$, $f_{C3}(RH)$ and $f_{C4}(W_c)$ are function of time, temperature, relative humidity, and width of the crack as explained in Chapter 3.

4-2-1 Validation of the Proposed Modelling of Chloride Penetration

Previous experimental studies have been used in verify the model. The research is classified based on the factors that influence the chloride penetration in reinforced concrete structures. Concrete characteristics (w/c ratio, cementitious materials kinds), crack width, relative humidity, and temperature are among them.

An integrated model was employed to estimate chloride penetration in this investigation.

Experimental data from the experimental program of literature investigations were used to validate the model. The model was based on

variations in the Cl^- diffusion coefficient as a result of changes in external and internal factors. These variables were used to simulate chloride concentration in concrete structures theoretically.

4-2-2 Effect of (w/c) on Chloride Concentration

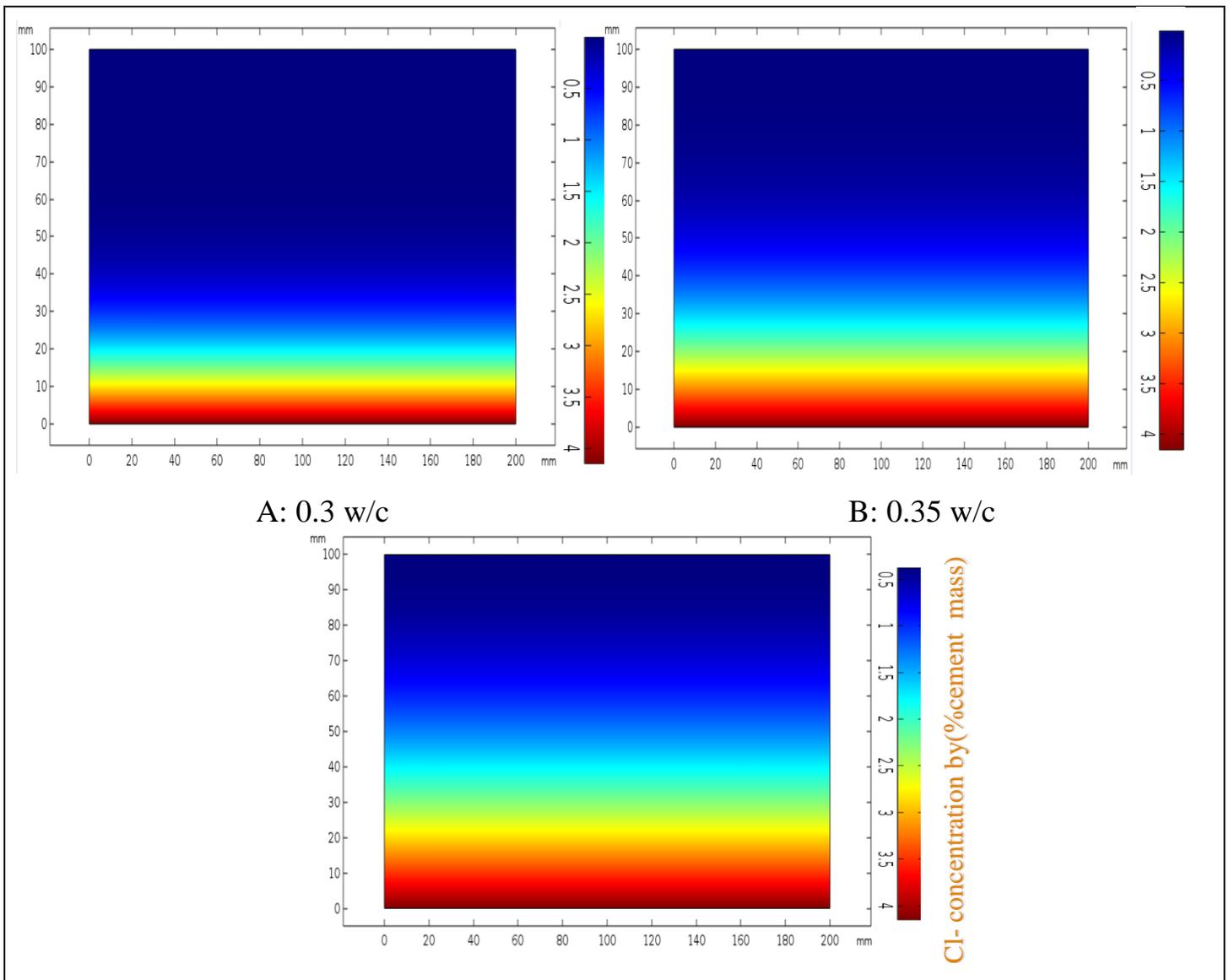
The chloride diffusion coefficients, Equations are used to determine Da_{cl^-} for various w/c ratios as shown the flowchart (3-1). Chloride diffusion in concrete is influenced by the concrete structures, specifically the porosity. The porosity is governed by the water-to-cement ratio, As the w/c ratio rises, the porosity rises as well. As a result, as shown in Figure (4-1), the diffusion of Cl^- ions inside the concrete rises. (Tang, 2003) and others show that the increase in w/c lead to an increase in the diffusion of chloride ions inside the concrete. As a result, increasing the porosity leading to an increase in pores, that work a faster path of ingress of chloride ions inside concrete.

Equation (4-1) and (4-2) models are applied and other factors has been explained in chapter 3, that consider the effect temperature, relative humidity, exposure time, crack width and properties of concrete.

The suggested model's results were compared to the results of the studies reviewed show that the diffusion of chloride ions coefficient increase Da_{cl^-} as shown in Table (4-1) and Figure (4-1),(4-2):

Table (4-1): Value of C_s and D_a depending on application models

Factor	w/c ratio	C_s by mass of cement	D_a ($m^2/s \cdot 10^{-12}$)
Water cement ratio	0.3 SRPC	4.15	4.559
	0.35 SRPC	-	6.011
	0.4 SRPC	-	7.923



C: 0.4 w/c

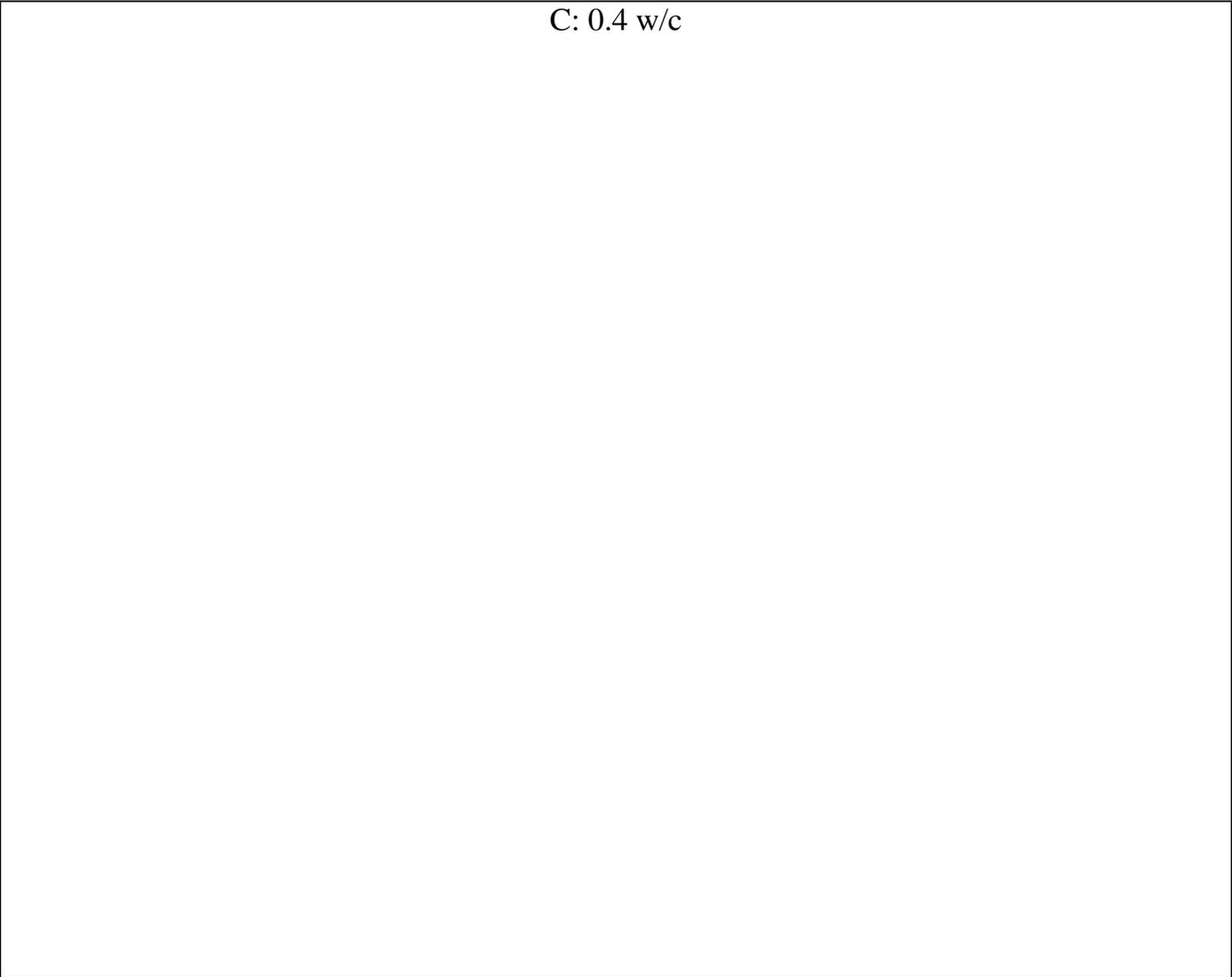


Figure (4-1): The distribution of chloride concentrations in sample.

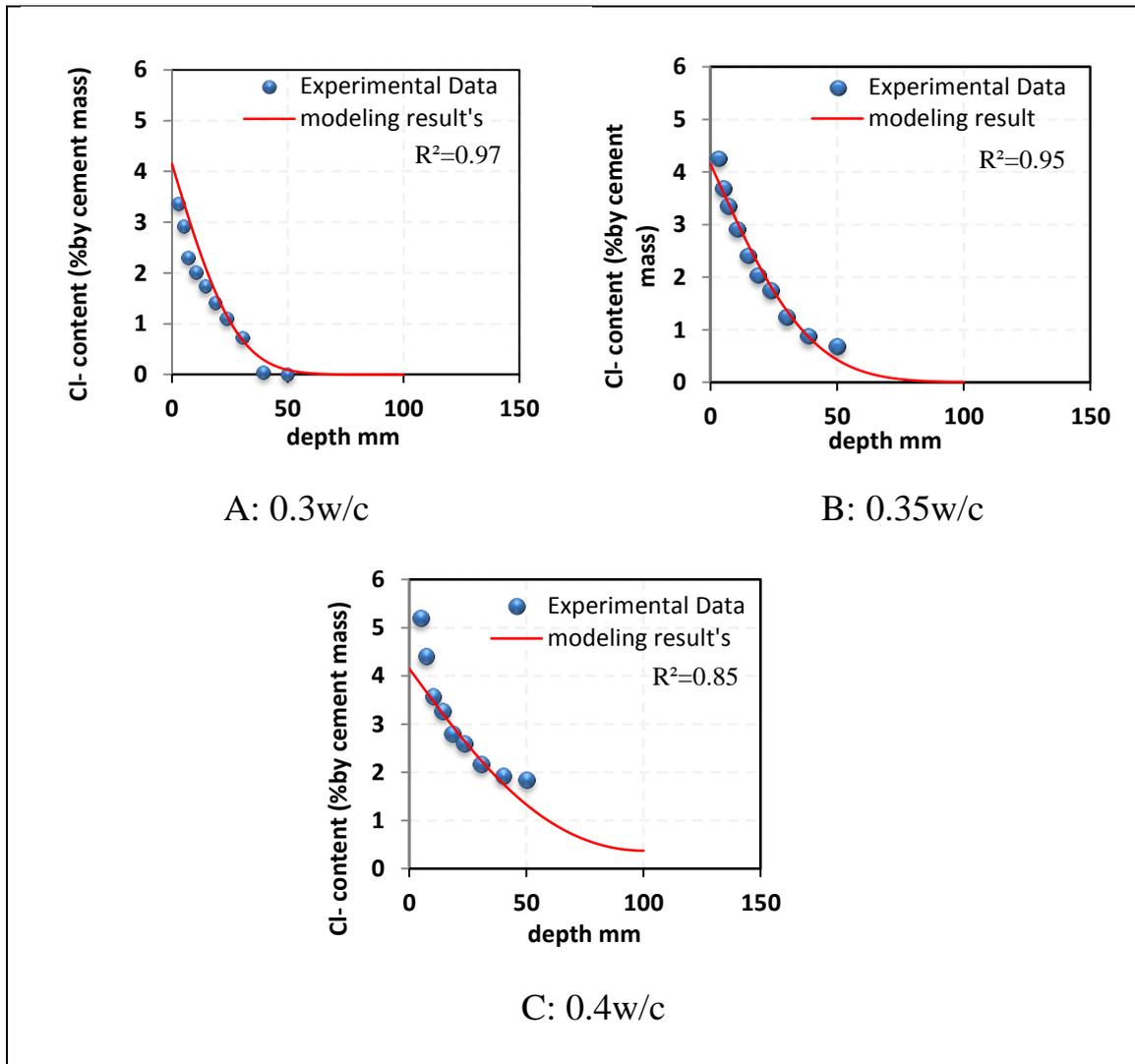


Figure (4-2): results of the model vs. the results of the experiments of (Tang,2003) for different w/c (A:0.3, B:0.35, C:0.4)

4-2-3 Effect of Crack Width on Chloride Concentration

After the water-to-cement ratio, the crack is the second most important influencing chloride ion penetration in concrete. An increase in the width of a concrete crack allows chloride ions to penetrate rapidly and diffusion into the concrete. Ishida (2009) suggested that Chloride movement is particularly rapid along and across crack profiles, as evidenced by two-dimensional chloride profiles along cracks in the experiment. Al-Ameeri *et al.*, (2021) showed that due to the comparatively faster penetration of Cl^-

into the fracture, chloride penetration in the area of the cracks is significantly higher.

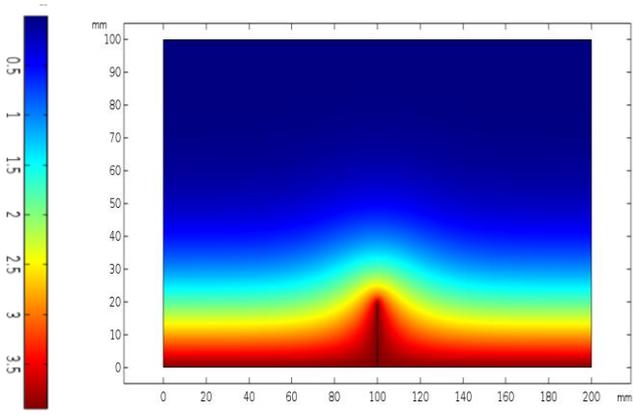
The proposed model's results were compared to the results of the studies are reviewed, as a case of seawater, show that the diffusion of chloride ions coefficient increase D_{act} as the crack width increase as shown in Table (4-2) and Figure (4-3), (4-5) and (4-6).

Table (4-2): Value of Cs and Da depending on application models

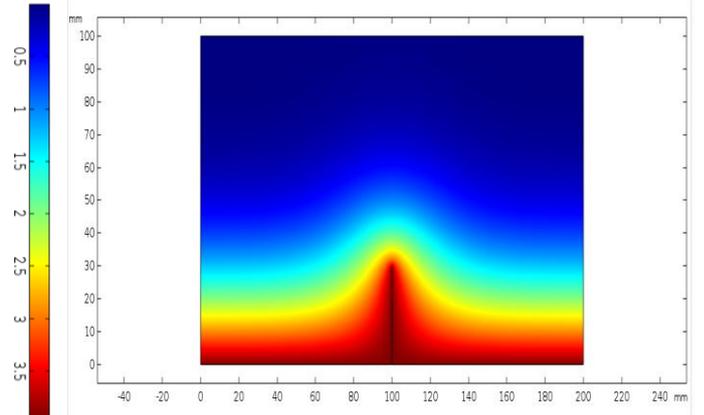
Factor	w/c ratio	Crack width	Cs By mass	Da ($m^2/s*10^{-12}$)	References
Water cement ratio & crack	0.6 OPC	0.1	3.9485	4.17452	(Al-Ameeri <i>et al.</i> , 2020)
		0.2		4.55033	
		0.35		5.15368	
	0.4 OPC	0.1		1.3823	
		0.2		1.5067	
Crack	0.39 OPC	0.2	3.85	7.10644	(Ishida, 2009)
	0.55 OPC			17.20	

CHAPTER FOUR OF CHLORIDE PENETRATION

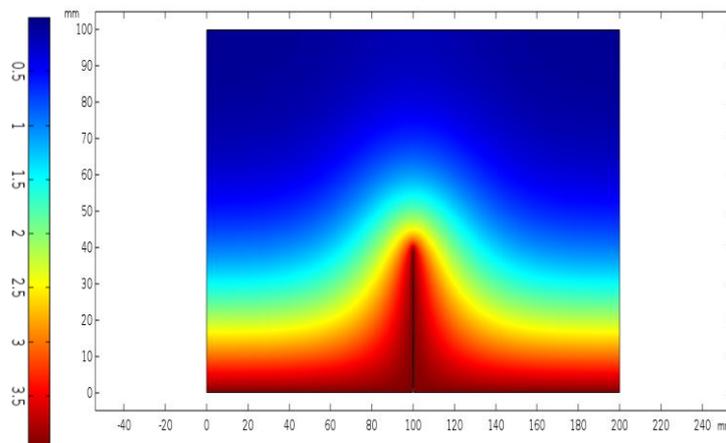
MODELLING RESULT AND DISCUSSION



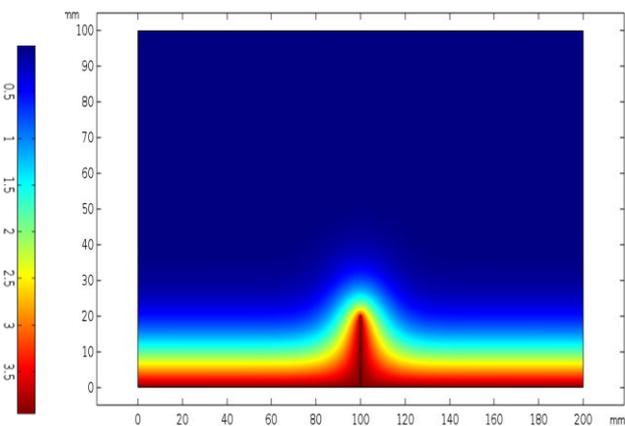
A: 0.6 w/c, Crack width 0.1



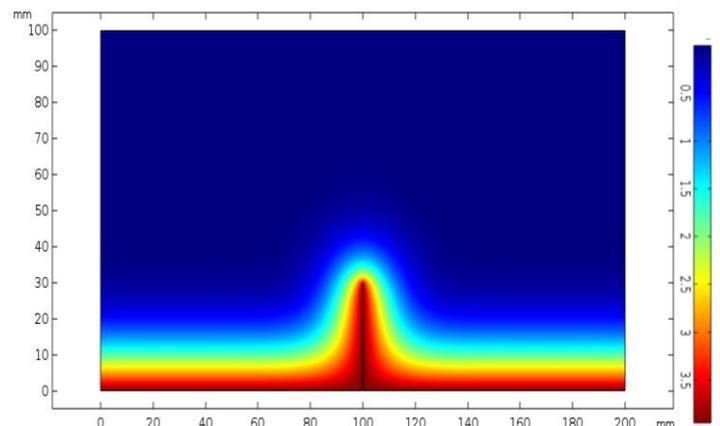
B: 0.6 w/c, crack width 0.2



C: 0.6 w/c, crack width 0.35



D: 0.4 w/c, crack width 0.1



E: 0.4 w/c, crack width 0.2

Figure (4-3): The distribution of chloride concentrations in samples with cracks after 105 days of exposure to a chloride environment at 25 °C

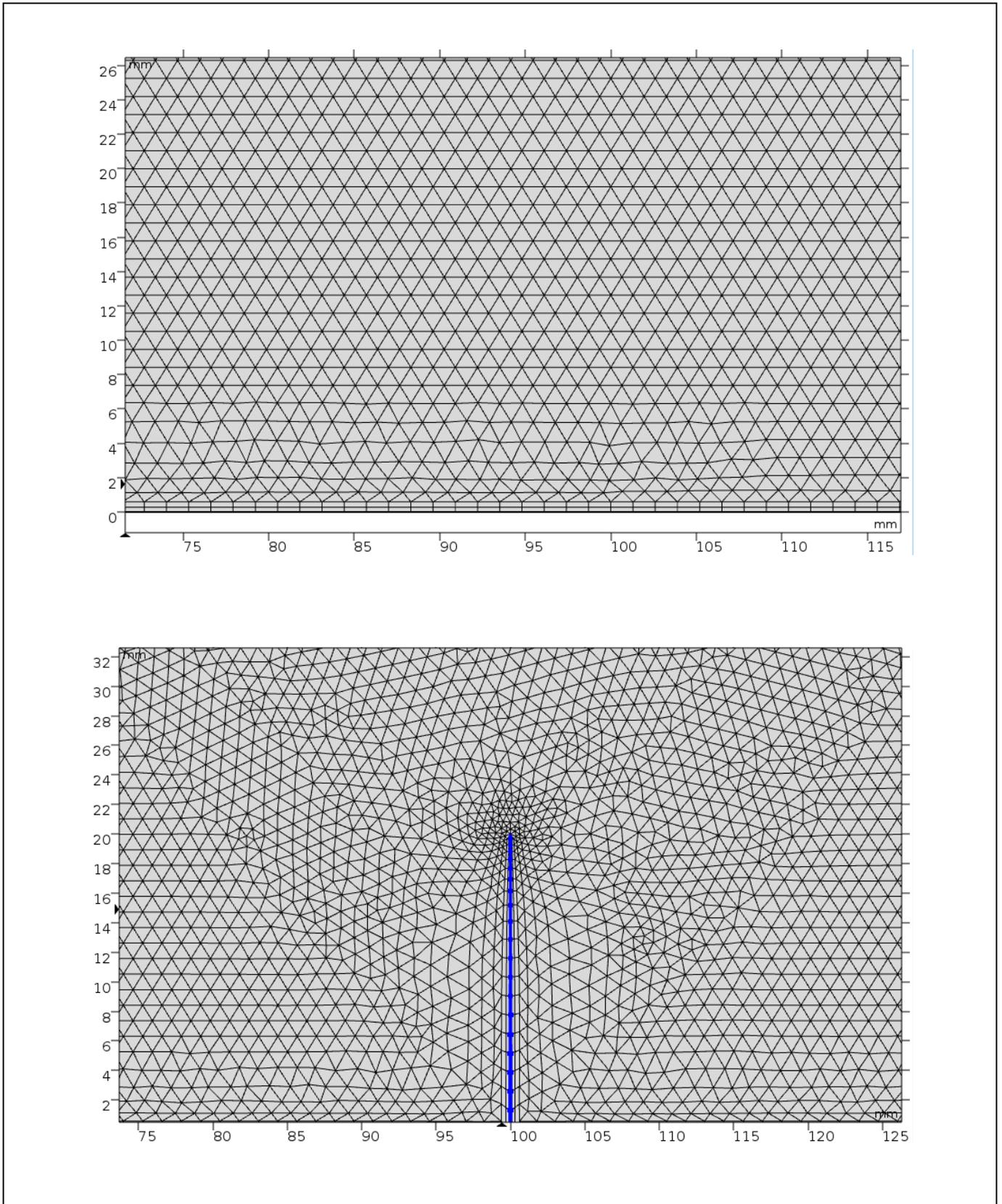


Figure (4-4): Mesh for crack and non-crack concrete

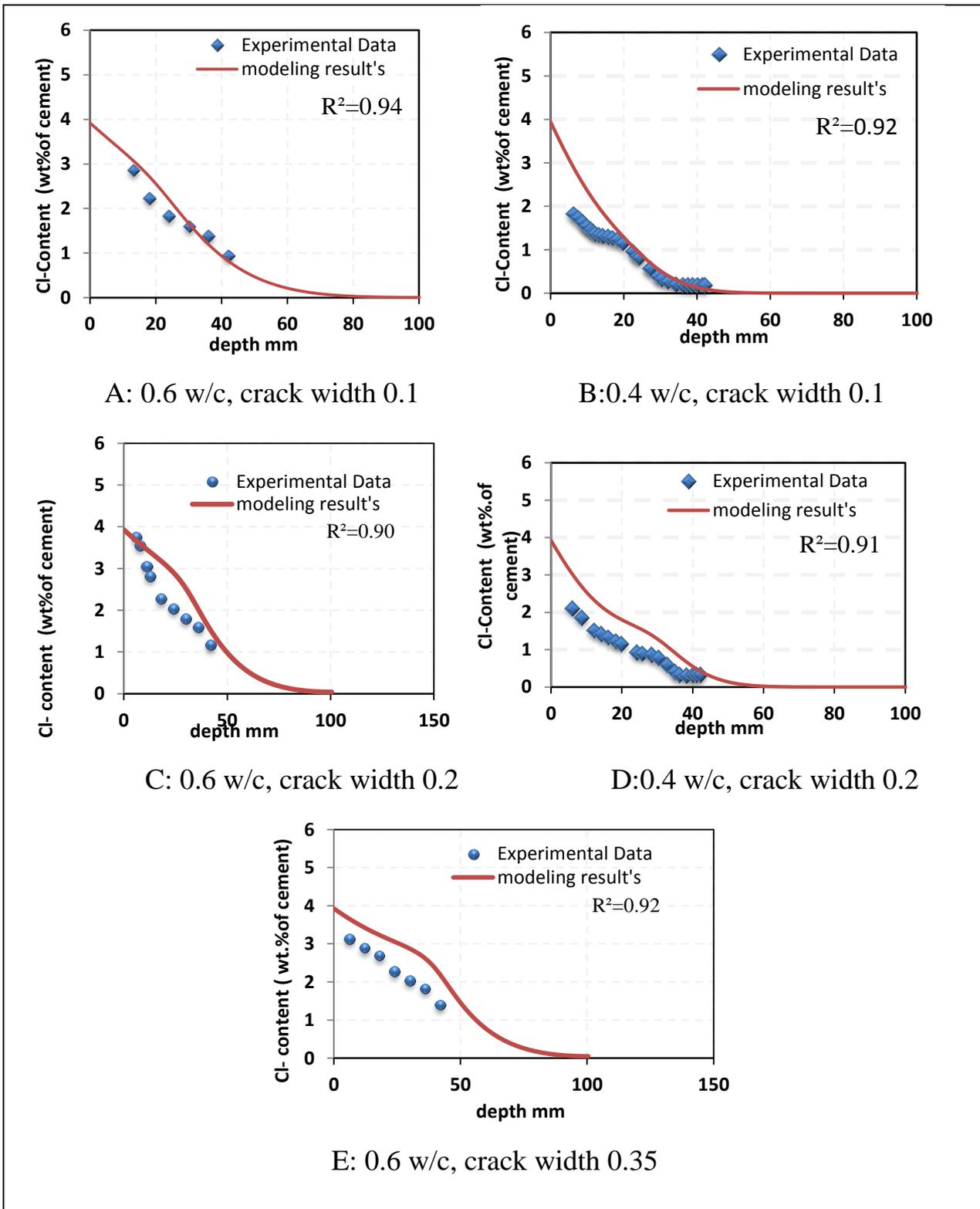


Figure (4-5): Comparison modeling result VS experimental results of AL-
Ameeri et al. (2021)

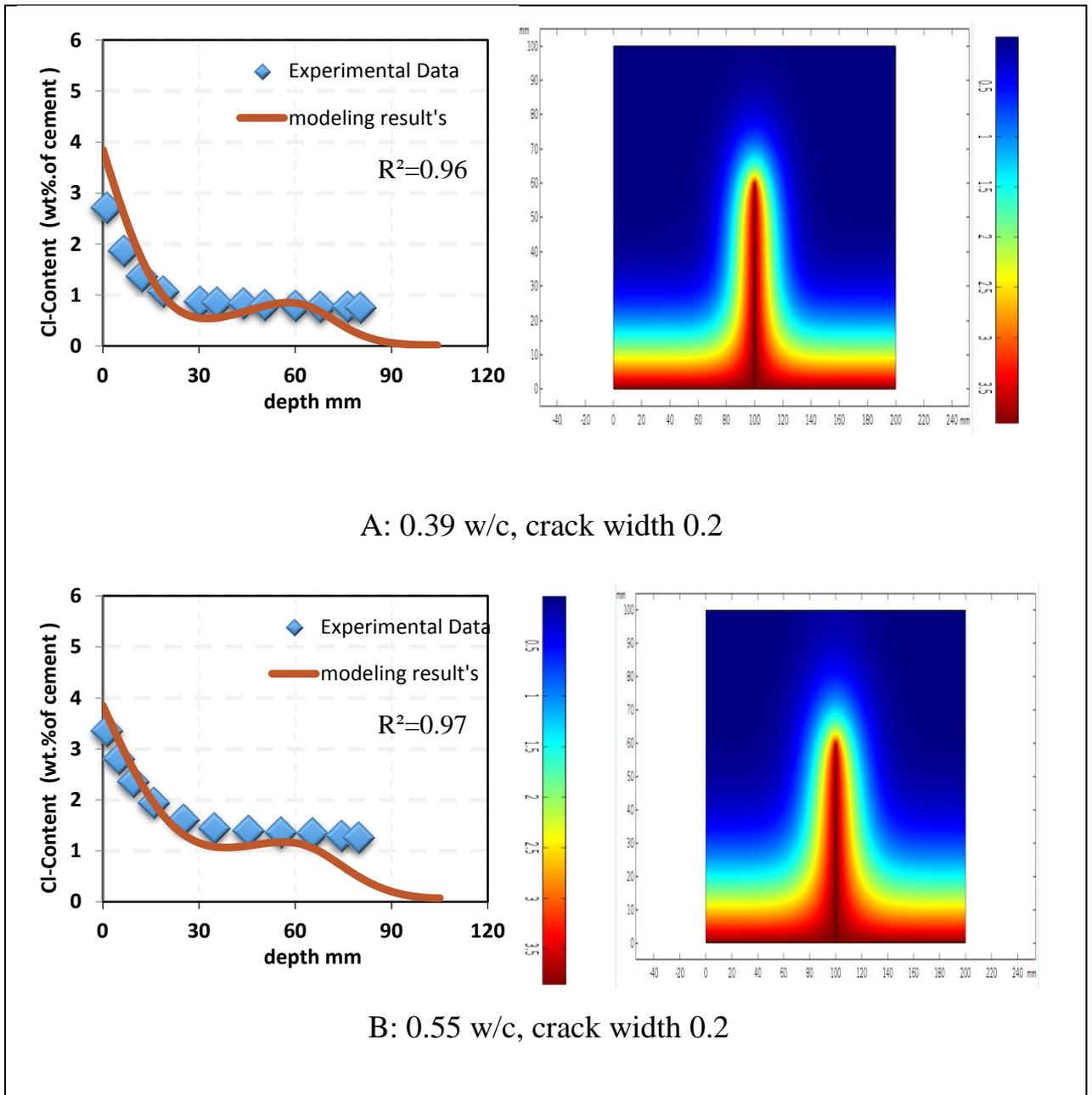


Figure (4-6): Comparison modeling result VS experimental results of [Ishida, \(2009\)](#) and the distribution of chloride concentration in sample with crack after 91 days of exposure to a chloride environment at 40°C

4-2-4 Effect of Relative Humidity on Chloride Concentration

The one essential component that influences chloride penetration and increases chloride concentration in concrete structures is relative humidity or moisture content. With an increase in relative humidity, the diffusion of chloride ions in concrete rises. Water vapor can fill pores in concrete, resulting in fluid water at a specific relative humidity. The chloride ion and oxygen are transported to the steel surface by pore water. According to [Bernal *et al.* \(2016\)](#) investigated, the chloride environmental content exposure to de-icing salts when the relative humidity 75% and 100%, with increase the humidity the diffusion chloride coefficient increase as shown in Table (4-3):

Table (4-3): Value of Cs and Da depending on application models

Factor	w/c ratio	RH%	Cs by mass	Da (m ² /s*10 ⁻¹²)
Relative humidity	0.4 OPC	100%	6.2	6.13
	-	75%	-	3.89
	0.45 OPC	100%	-	8.083

The suggested model's results were compared with the results of other studies where showed that the diffusion of chloride ions coefficient increase D_{acl^-} as RH% increase as shown in Figure (4-7):

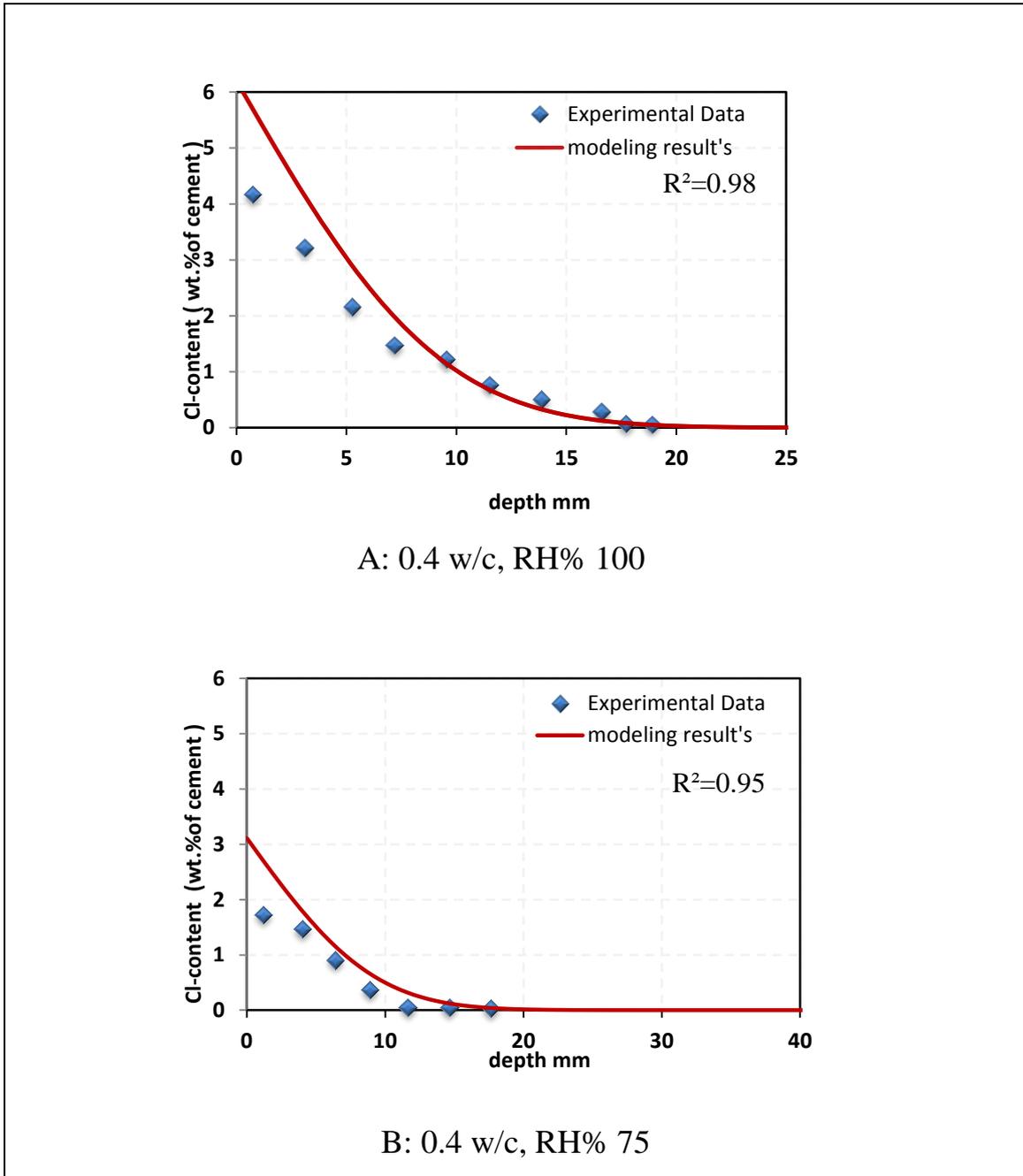


Figure (4-7): Comparison modeling result VS experimental results of **Bernal et al. (2016)**

4-2-5 Effect of Temperature on Chloride Concentration

As the temperature rises, the chemical bonds between chloride ions dissolve, resulting in an increase in free chlorides, which are responsible for the damage. In general, temperature has a significant impact on chloride ion diffusion, resulting in an increase in diffusion coefficient as temperature rises, as illustrated in Table (4-4).

Zhiming(2016) investigated the effect of high temperature on chloride penetration, The damage increases during the temperature above of 400°C. The results show that when temperatures rise, the maximum chloride content rises, and that this rise is accompanied by an increase in the maximum chloride content.

Figure (4-8) and (4-9) show the comparing the experimental result with proposed model results.

Table (4-4): Value of Cs and Da depending on application models

Factor	w/c ratio	T°C	Cs	Da(m ² /s*10 ⁻¹²)	
Water cement ratio & Temperature	0.4 OPC	20°C	0.827	6.819	
		200°C		6.828	
		600°C		6.835	
	0.5 OPC	20°C	0.87	11.85	
		200°C			11.867
		600°C			11.878

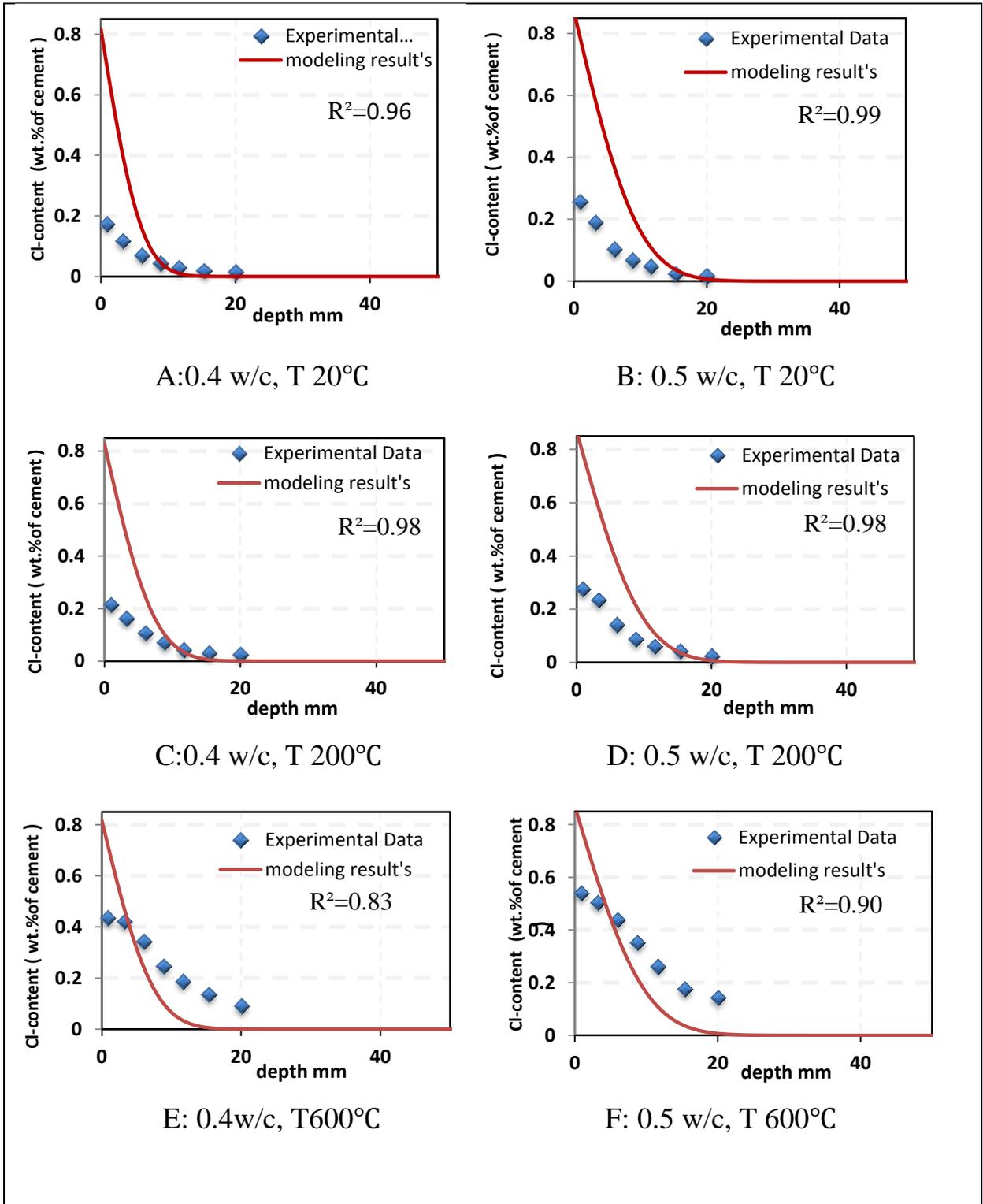


Figure (4-8): Comparison modeling result VS experimental result of

Zhiming(2019)

4-2-6 Effect of Supplementary Cementitious Material on Chloride Concentration

Supplementary cementitious materials are used to replace part of the cement with chemical or mineral additives, which react with calcium hydroxide, $Ca(OH)_2$ released by cement hydration to form calcium silicate hydrate, which is responsible for the bond between aggregate parts. Some additives are also used to reduce w/c , making the concrete more durable and less permeable.

Bernal et al.(2016) studied the concrete exposed to de-icing salt and **Tang, (2003)** investigated the source of chloride is seawater according to the previous research show the use of cementitious material lead to decrease diffusion chloride coefficient as shown in Table (4-5). By applying the proposed model in Chapter 3 for silica fume is used Equation (3-4), for blast furnace slag is used Equation (3-5), Figure (4-9) presents the comparison between the results of **Bernal et al.(2016)** and **Tang(2003)** with results of proposed model.

Table (4-5): Value of C_s and D_a depending on application models

Factor	w/c ratio	SCMs	C_s	$D_a(m^2/s*10^{-12})$	references
Supplementary cementitious materials	0.45OPC	20% BFS	6.2	7.1029	Bernal et al, (2016)
	0.45 OPC	10% SF	3.11	$9.85*10^{-13}$	
Supplementary cementitious materials	0.35SRPC	5% SF	4.15	2.63	Tang(2003)
	0.4 SRPC	5% SF		3.47	

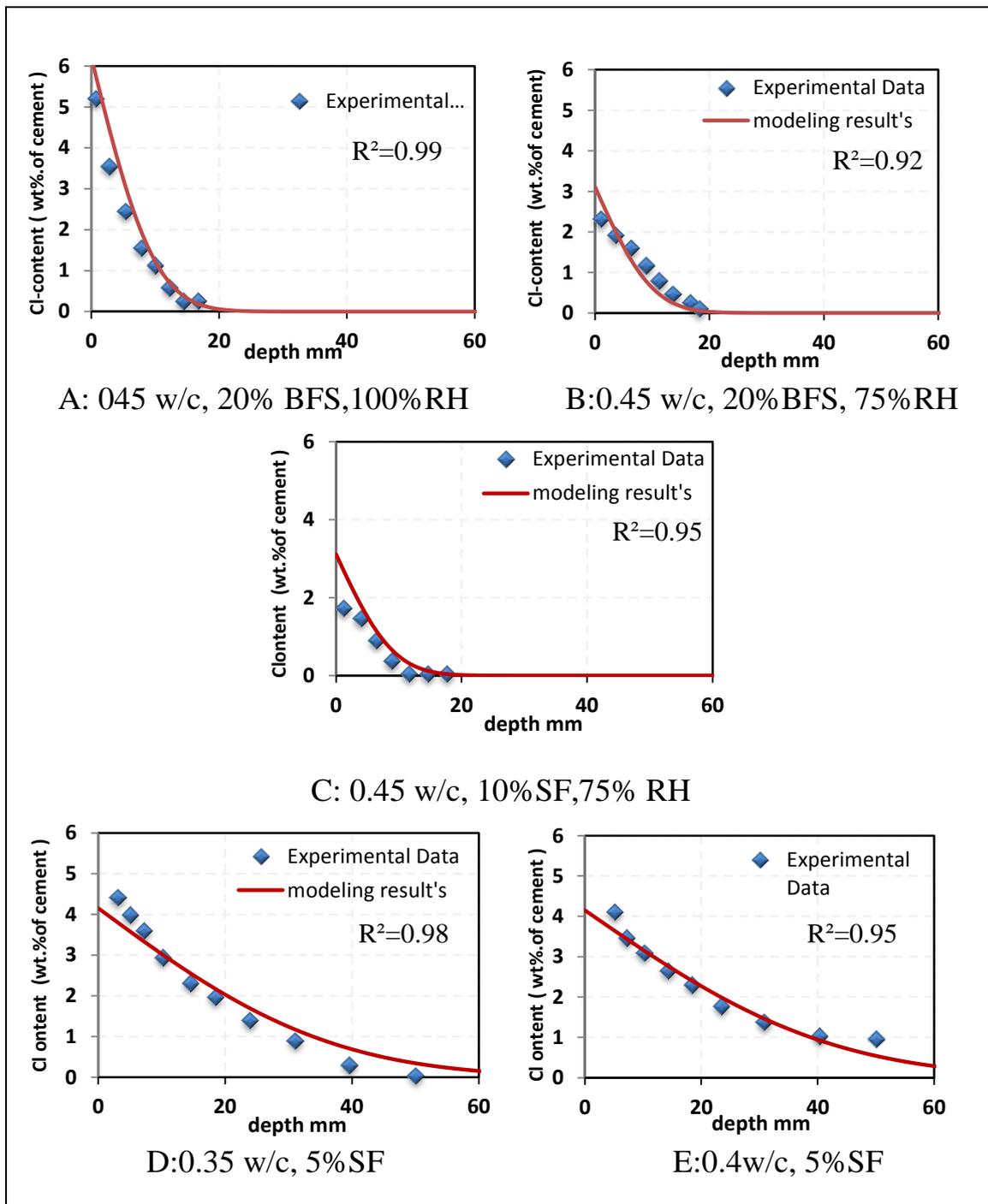


Figure (4-9): Comparison modeling result VS experimental result of **Bernal et al.(2016)(A, B, C)** and **Tang(2003)(D, E)**

4-2-7 Model Reliability Based on Previous Experimental Results

Figures (4-2), (4-5), (4-6), (4-7), (4-8), and (4-9) show that the predicted data resulting from modeling matches the experimental data from researcher well as shown in Table (4-6).

Table (4-6) Summary of regression of model data and experimental results

Factor	concrete mix	R ²	references
Water cement ratio	0.3 SRPC	0.97	Tang,2003
	0.35 SRPC	0.95	
	0.4 SRPC	0.85	
Water cement ratio & Crack	A- 0.6 OPC	0.94	AL-Ameeri et al, 2021
	C- 0.6 OPC	0.90	
	E- 0.6 OPC	0.92	
	B- 0.4 OPC	0.92	
	D- 0.4 OPC	0.91	
Water cement ratio & crack	0.39 OPC	0.96	Ishida,2009
	0.55 OPC	0.97	
Relative Humidity	0.4 OPC	0.98	Bernal et al.,2016
	0.45 OPC	0.95	
Temperature (T)	A- 0.4 OPC	0.96	Zhiming,2016
	C- 0.4 OPC	0.98	
	E- 0.4 OPC	0.83	
	B- 0.5 OPC	0.99	
	D- 0.5 OPC	0.98	
	F- 0.5 OPC	0.90	

Supplementary	A-0.45 OPC+20%BFS	0.99	Bernal et al.,2016
Cementitious	B-0.45 OPC+20%BFS	0.92	
Material	C-0.45 OPC+10 SF	0.95	
(SCMs)	D-0.35 OPC+5 SF	0.98	Tang,2003
	E-0.35 OPC+5 SF	0.95	

When previous research results were compared to the proposed model's results, it is observed a little difference in some cases and a significant difference in others, but all values are more than regression value of 0.83. Overall, this model can be used to predict chloride penetration in concrete for various crack widths and exposure conditions (e.g. time exposure, temperature, and relative humidity).

4-3 Prediction of Chloride Penetration in Concrete Structure due to Climate Change using Proposed Model

As mention in chapter 2, *GHG* emissions are increasing, and carbon dioxide is one of the most important gases contributing to climate change and global warming (IPCC,2014), The greenhouse effect is being aggravated by greenhouse gas emissions, which is causing the Earth's surface temperature to rise (EPA, 2017). Thus, the climate change has significant impact, to accelerate the ingress of *Cl* ions in (*RC*) structures. this section deals with chloride diffusion coefficient due to climate change in concrete structures according to environment exposure as a numerical prediction. There are two cases in which the proposed model will be applied to predict the future condition, the first one is exposed to seawater and the other to groundwater. The city of was chosen because of its high temperature and humidity. These conditions encourage chloride penetration into concrete structures.

In this case, the chloride penetration in reinforced concrete structures related to this exposed environment condition (temperature, relative humidity, and climate change scenario (IPCC,2014) was predicted using hypothetical samples of concrete structures in the city of Basra and AL-Najaf. The following calculations and assumptions will be applied in accordance with the penetration methodology given in Chapter 3:

A: Structure Exposure to Marine Environment

1. Properties of concrete

- w/c ratio = 0.5, total density 2400 kg/m³, cement content 450 kg/m³, water content 225 kg/m³
- The initial chloride concentration ($C_i = 0$)

2. Exposure condition

- In marine environment, the chloride concentration is 1.9 %
- Temperature as shown in Figure (4-10), its represented the annual change of the temperature in the city of Basra, due to climate change take in account the worst case RPC 8.5
- Relative humidity as shown in Figure (4-10), it will assume constant about 95% due to the structure exposure to marine environment

3. Exposure time: (25 and 50 years)

4. The diffusion coefficient of chloride ($D_{a_{cl^-}}$): is calculated from Equation (3-2 to 3-9) take into consideration the factor of age of concrete, temperature, relative humidity and crack width.

5. The surface concentration of chloride (C_s): according to service life ACI-365 the concentration after 10 years will be constant as shown in Figure (3-2), C_s will rich 1% (weight of concrete), the surface

concentration of chloride will be change over time exposure according to the equation Song

- The shape of concrete is pier have thickness and width, 200,400 mm respectively with cover of concrete is 50mm

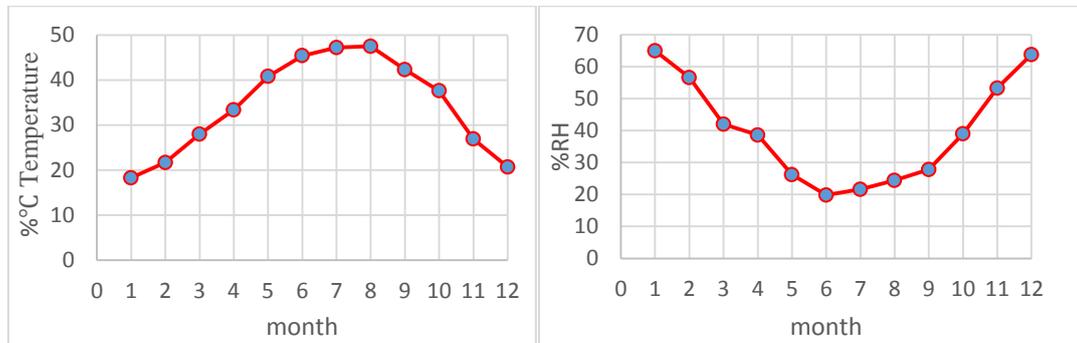


Figure (4-10): The average maximum temperature and relative humidity of Basra city for the last 10 years

By applied all above assumptions for pier structures in city of Basra (Shatt al, Arab) exposure to marine environment, by take in account the age of concrete, Temperature, relative humidity and crack width (0.1 mm) with climate change according to the seniors of (IPCC,2014), by change in temperature. the predicted result show that by increase in temperature the chloride diffusion coefficient increase as show in Table (4-7) Table (4-7):Value for C_s and D_a for application models To marine environment.

Sample	D_a & C_s (D_a values * 10^{-12})							
	after 25Y Withoutcc		After 25Y with cc		after50 y without cc		after 50 y with cc	
	C_s	D_a	C_s	D_a	C_s	D_a	C_s	D_a
0.5 w/c Uncracked	1	8.4	1	9.45	1	8.4	1	13.3
0.5w/c Cracked	1	9.22	1	13	1	9.22	1	17.1

Cs: surface concentration of chloride by the mass of concrete

The experimental results are presented in Figure (4-11) (4-12) after utilizing the equations and the COMSOL program.

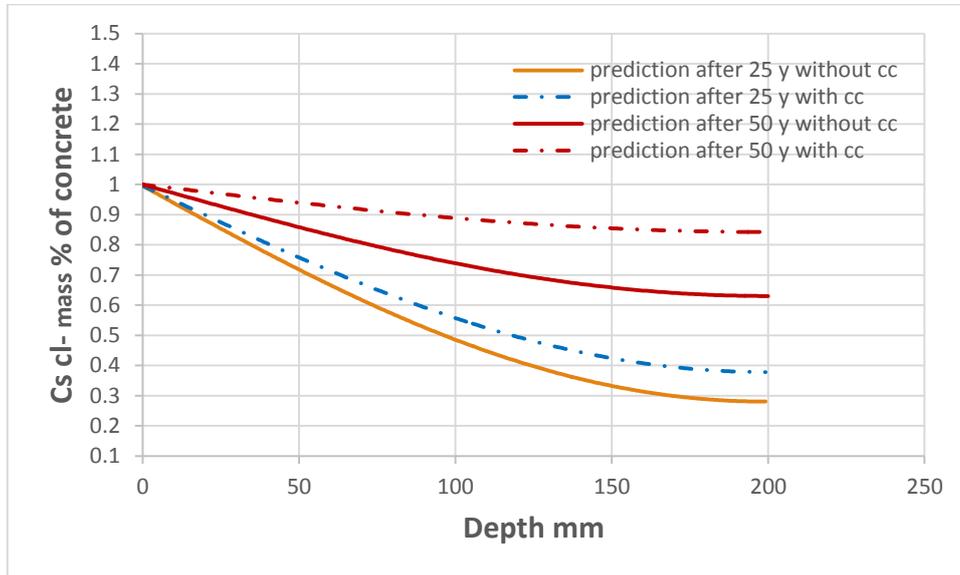


Figure (4-11): Prediction of chloride penetration after 25 and 50 years with and without climate change according to **ACI-365**

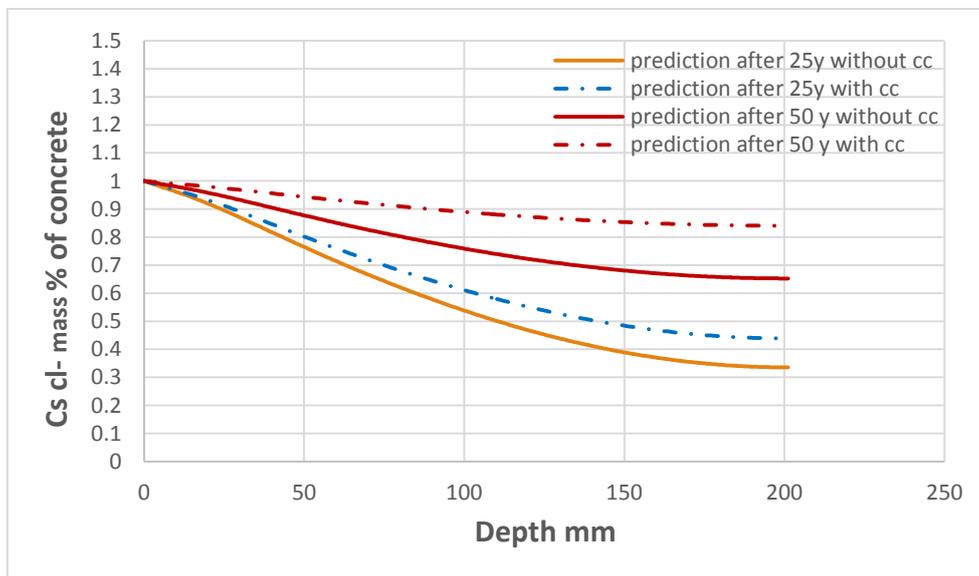


Figure (4-12): Prediction of chloride penetration after 25 and 50 years with and without climate change according to **ACI-365** with 0.1 mm width crack

B- Structures Exposed to Groundwater

1. Properties of concrete
 - w/c ratio 0.4, total density 2400 kg/m^3 , cement content 513 kg/m^3 with water content 205 kg/m^3
 - initial concentration content ($C_i=0$)
2. exposure condition
 - **Tawfek(2017)** concentrations data in soil will use the condition of sample. The reference samples are exposed to water with a *NaCl* concentration of 4 mg/l (normal water) to aid in the oxidation process, whereas the other samples are cured in salty water with a *NaCl* concentration of 4000 mg/l to aid in the oxidation process (a doubled value of the concentration of *NaCl* in ground water of AL-Najaf city in Iraq)
 - Temperature is shown in Figure (4-13), its represented the annual change of the temperature in the city of AL-Najaf, due to climate change take in account the worst case (RPC 8.5).The temperature is five degrees lower than the surface temperature, depending on the layers of the soil.
 - Relative humidity as shown in Figure (4-13), it will assume constant about 95% due to the structure exposure to Groundwater
3. Exposure time: (25 and 50 years)
4. The diffusion coefficient of chloride (D_{acl^-}): is calculated from Equation (3-2 to 3-9) take into consideration the factor of age of concrete, temperature, relative humidity and crack width.
5. The surface concentration of chloride (C_s): according to service life ACI-365 the concentration after 10 years will be constant as shown in Figure (3-2), C_s will rich 1% (weight of concrete), the surface

concentration of chloride will be change over time exposure according to the equation Song

- The shape of concrete is culvert have cross-section dimension with thickness and width 300,400 mm

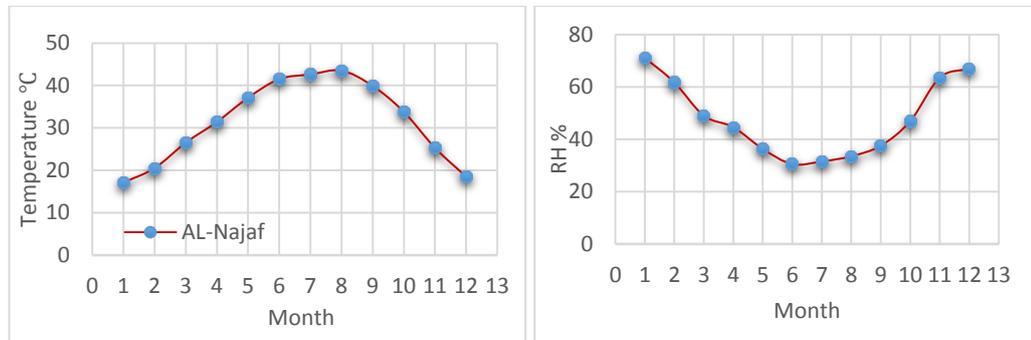


Figure (4-13): The average of maximum temperature and relative humidity of AL-Najaf city for the last 10 years

By applied all above assumptions for culvert structures in city of AL-Najaf exposure to Groundwater environment, by taking in account the age of concrete, temperature, relative humidity and crack width (0.1 mm) with climate change according to the seniors of (IPCC,2014), by change in temperature. the predicted result show that by increase in temperature the chloride diffusion coefficient increase as show in Table (4-8)

Table (4-8): Value for C_s and D_a For application models to groundwater environment

Sample	D_a & C_s (D_a values * 10^{-12})							
	after 25Y Withoutcc		after 25 y with cc		after 50 y without cc		after 50 y with cc	
	C_s	D_a	C_s	D_a	C_s	D_a	C_s	D_a
0.4 w/c Uncracked	1	3.4	1	4.5	1	3.4	1	7
0.4w/c Cracked	1	3.73	1	5	1	3.73	1	8.4

C_s : surface concentration of chloride by the mass of concrete

After using the equations and the COMSOL program, the experimental results are shown in the figure (4-14), (4-15).

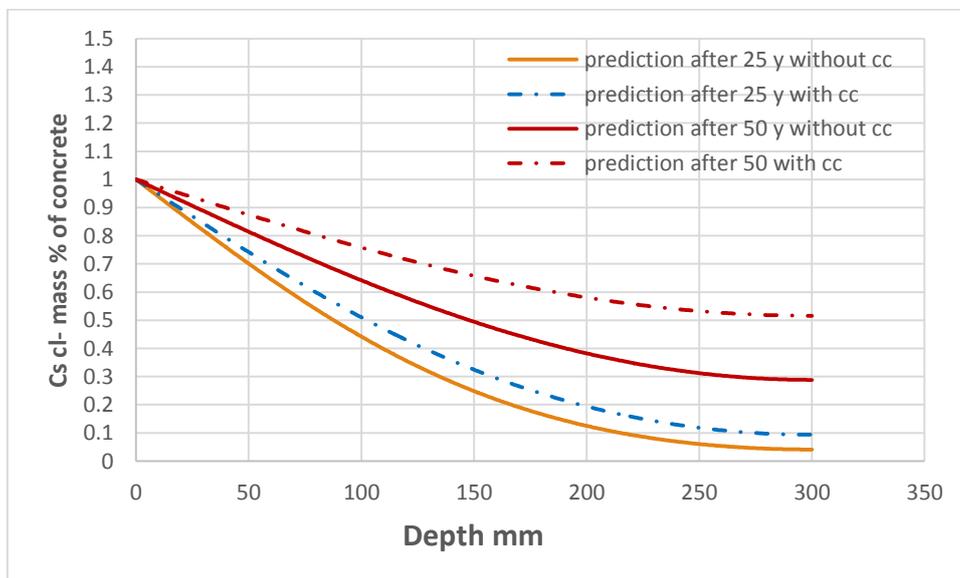


Figure (4-14): Prediction of chloride penetration after 25 and 50 years with and without climate change according to **ACI-365**

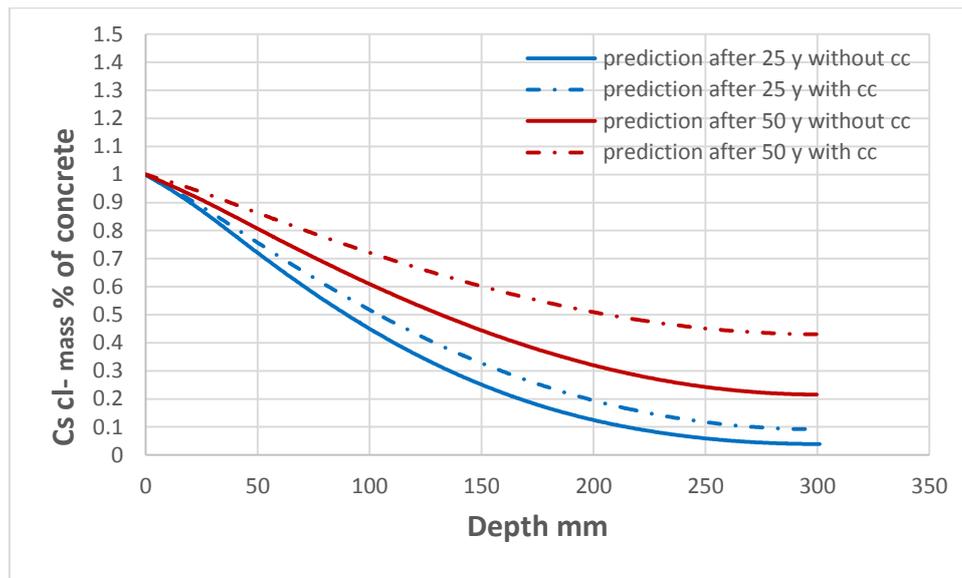


Figure (4-15): Prediction of chloride penetration after 25 and 50 years with and without climate change according to ACI-365 with 0.1 mm width crack

After applying the models to both cases A and B and taking into consideration the assumptions described above (seawater environment and groundwater environment), The study established that the level of chloride in the concrete is greatly influenced by changes in temperature as a result of climate change according to the senior (IPCC,2014), (AR5, RPC 8.5) (the Temperature increase 4°C), the period of exposure, and the quality of the concrete without or with the crack.

The propagation of the chloride content concentration is observed at the time of exposure 50 year with an increase in temperature and the exposure period is higher than the concentrations of chloride content at the time of exposure 25 year .

When it comes to structures that are exposed to the seawater, The percentage rise in chloride concentration at depths of 50 mm is 1%, 4.9 percent for exposures of 25 and 50 years, respectively, whereas the percentage increase in chloride concentration for cracks (0.1 mm and deep 20mm) is 3.7 percent, 7.7% for exposures of 25 and 50 years.

When it comes to structures that are exposed to groundwater, for exposures of 25 and 50 years, the percentage rise in chloride concentration at depth 50 mm is 1%, 3.6 %, respectively, whereas the percentage increase in chloride concentration for cracks (0.1 mm and deep 20mm) and it was 1.2% and 4.7 %, respectively.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS AND RECOMMENDATIONS

5-1 CONCLUSIONS

The purpose of this research is to find a theoretical model to predict the chloride penetration in concrete structures. The study is conducted out with the use of specific penetration models that account some variables such as temperature, relative humidity, concrete age, crack width and climate change that encourage chloride to penetrate reinforced concrete structures and attack steel reinforcement. After confirming the prediction performance by comparing the results to previous studies and applying the models on structures subjected to marine and groundwater environments using an experimental program (COMSOL Multiphysics). The following conclusions can be settled based on the results reached:

1. An integrated model has been suggested to simulate chloride concentration in concrete structures constructed completely by ordinary Portland cement or containing supplementary cementitious materials and taking climatic change over time, temperature, relative humidity, and crack width into consideration.
2. The results of the integrated model showed a good matching with the results of experimental researches. Therefore, an integrated model can be utilized to predict chloride concentration in reinforced concrete structures for different cases.

3. The research has acknowledged the previous studies, which included increasing chloride penetration and concentration by increasing temperature, crack width, relative humidity, and the water- cement ratio.
4. When the relative humidity is constant, chloride penetration increases as the chloride ion concentrations increase with time and temperature.
5. The chloride concentration maybe increase when taking climate change scenarios of IPCC, 2014 into consideration over time, temperature, relative humidity.
6. At the time of exposure 50 years, the chloride content concentration propagates with an increase in temperature, and the exposure period is longer than the chloride content concentrations at the time of exposure 25 years.

5-2 RECOMMENDATIONS

1. Putting to put the current theoretical study into practice and see how the outcomes correspond.
2. It requires a thorough examination of relative humidity, as well as an appreciation of the changes that will occur in the next years and study the impact on this model.
3. Study and develop of the present model, considering concrete under loading into account.

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Appendix A

A-1 Apparent Chloride Diffusion and Surface concentration of Cementitious Mixtures

The total chloride concentration profile is used to find apparent diffusion coefficient, D_a and surface concentration, C_s according to **BS EN 12390-11:2015** or **ASTM C 1556-11a: 2016**.

The D_a and C_s can be found by the least square difference between the experimental results of chloride concentration profile and the non-linear best fitting of Fick's Second Law of Equation (A.1), as shown in Table (A-1) and Figure (A.1).

$$C(x, t) = C_i + (C_s - C_i) \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_a \cdot t}} \right) \right] \quad (\text{A.1})$$

where:

$C(x, t)$ is the chloride concentration at depth (x) with time t ; C_i is initial chloride concentration (% mass of concrete); C_s is the surface chloride concentration (% mass of concrete); D_a is the diffusion coefficient of chlorides (m^2/sec); erf is the error function for solution of partial equation. To estimate experimental data by using equation.

Table (A-1) Chloride profile used to find D_a and C_s

C_s (mass%)	C_i (mass%)	D_a (m^2/s)	t (yr)	Sum(Error) ²
4.2	0	3E^{-12}	5	0.349417
x (mm)	Measured Value	Predicted Value	Sum, c(n) (Meas.-Pred.)	(Error) ²
3	4.26	3.90	0.36	0.1296
5	3.70	3.71	-0.01	0.0017
7	3.35	3.51	-0.16	0.0256
10	2.92	3.10	-0.18	0.0324
15	2.41	2.66	-0.25	0.0625
19	2.04	2.26	-0.22	0.0484
24	1.75	1.82	-0.07	0.0049
30	1.25	1.33	-0.08	0.0064
39	0.88	0.88	0.00	0.0000
50	0.70	0.44	0.26	0.0676

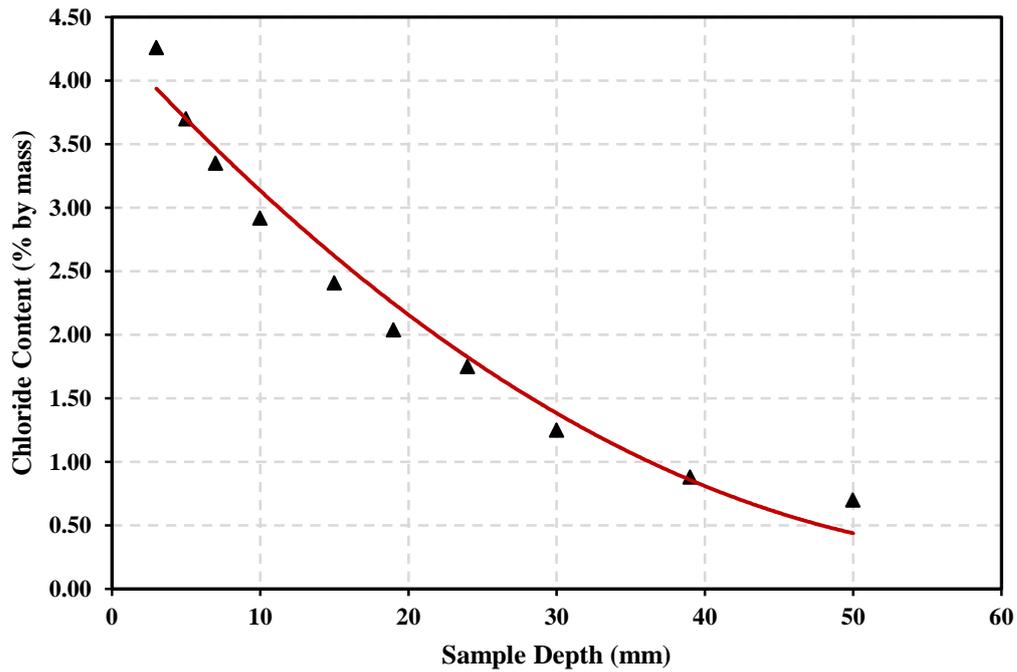


Figure (A. 1): The chloride profile with fitted curves for surface chloride content **BS EN 12390-11:2015** or **ASTM C 1556-11a: 2016**

A-2 Model Results

By using proposed model, the results of was found as shown in Table (A-2)

Table (A-2) Model Results

Cs(mass%)	C _i (mass%)	Da(m ² /s)	t (yr)
4.1	0	6*10 ⁻¹²	5

x(mm)	found Value by model	x(mm)	found Value by model	x(mm)	found Value by model
0.00	4.150	38.93	0.855	74.75	0.063
0.26	4.122	39.99	0.805	75.80	0.057
0.58	4.088	41.04	0.757	76.85	0.052
1.14	4.028	42.09	0.712	77.90	0.047
1.75	3.963	43.14	0.668	78.95	0.043
1.83	3.954	44.19	0.626	80.01	0.039
2.01	3.935	45.25	0.587	81.06	0.035
2.80	3.850	46.24	0.551	82.11	0.032
3.68	3.756	46.31	0.549	83.16	0.029
3.86	3.737	46.39	0.546	84.22	0.027
4.03	3.720	47.36	0.513	85.27	0.024
5.17	3.598	48.11	0.489	86.32	0.022
6.31	3.478	48.42	0.479	87.37	0.020
7.37	3.368	48.82	0.466	88.42	0.018
8.42	3.259	49.47	0.447	89.48	0.017
9.47	3.151	49.95	0.433	90.53	0.016
10.52	3.044	50.53	0.416	91.58	0.014
11.58	2.938	51.30	0.395	92.60	0.013

x(mm)	found Value by model	x(mm)	found Value by model	x(mm)	found Value by model
12.63	2.833	51.59	0.387	93.61	0.013
13.68	2.730	51.80	0.382	93.65	0.013
14.73	2.629	52.64	0.360	93.70	0.012
15.78	2.529	53.65	0.336	94.78	0.012
16.84	2.430	53.70	0.335	95.87	0.011
17.89	2.334	53.74	0.334	96.01	0.011
18.94	2.239	54.75	0.310	96.20	0.011
19.99	2.146	55.81	0.288	97.13	0.011
21.05	2.056	56.86	0.267	97.91	0.010
22.10	1.967	57.91	0.247	98.00	0.010
23.15	1.881	58.96	0.228	98.06	0.010
24.20	1.796	60.01	0.211	98.85	0.010
25.25	1.714	61.07	0.194	99.42	0.010
26.31	1.634	62.12	0.179	99.74	0.010
27.36	1.556	63.17	0.165	100.00	0.010
28.41	1.481	64.22	0.152		
29.46	1.408	65.28	0.139		
30.52	1.337	66.33	0.128		
31.57	1.269	67.38	0.117		
32.62	1.203	68.43	0.108		
33.67	1.139	69.48	0.099		
34.72	1.078	70.54	0.090		
35.78	1.019	71.59	0.082		
36.83	0.962	72.64	0.075		
37.88	0.908	73.69	0.069		

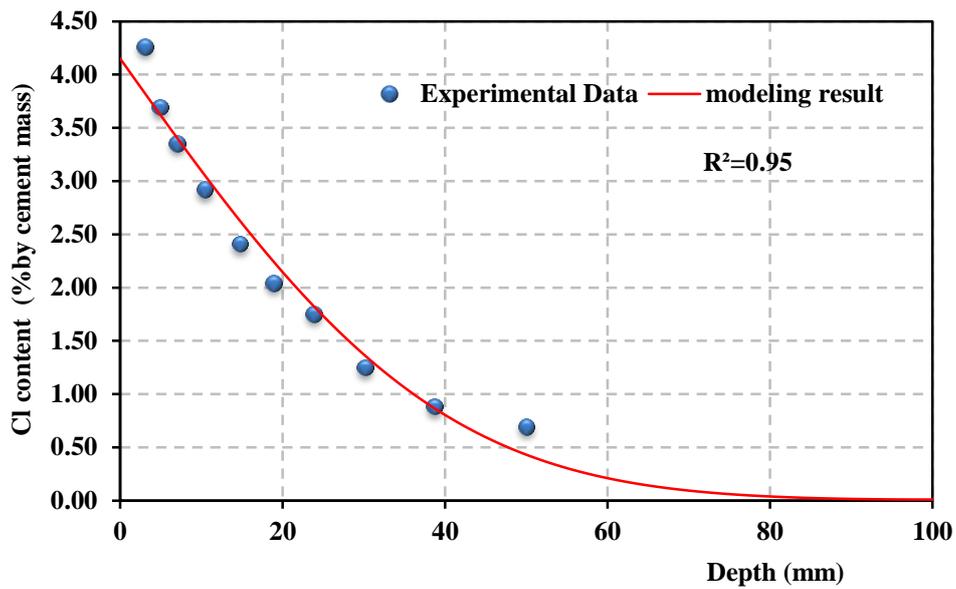


Figure (A-2) Experimental results of Tang (2003) and model data

- To find regression between Experimental results of Tang (2003) and model data as shown Figure (A-3).

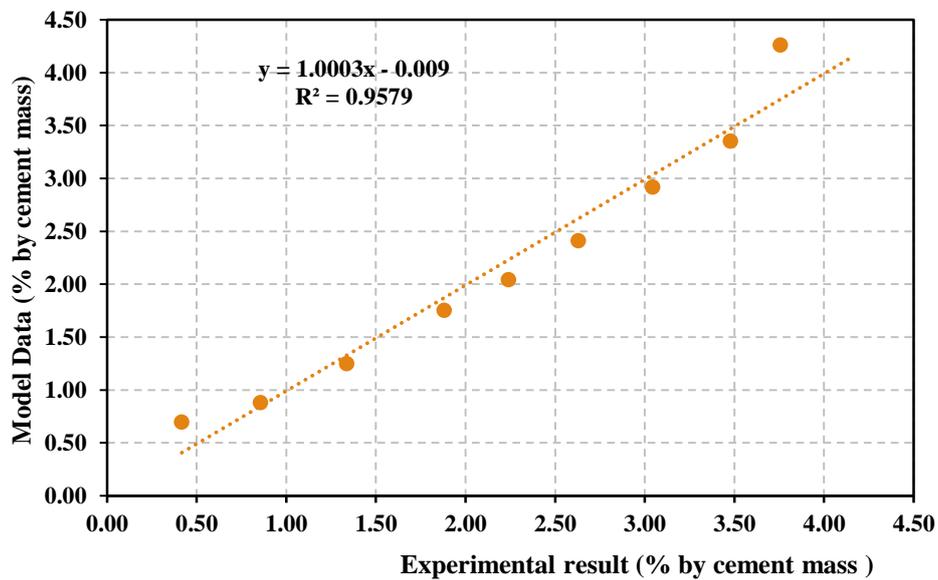


Figure (A-3) Regression between experimental data and modeling result

الخلاصة

يعتبر التنبأ بعمر الخدمة أحد أهم القضايا في تصميم الهيكل الخرساني حالياً. يجب أن يعتمد تصميم المتانة على نماذج موثوقة يمكنها أن تميز بشكل أكثر دقة آليات التدهور. أصبحت الخرسانة واحدة من أكثر مفاهيم البناء شيوعاً في العالم بسبب مزيجها الفريد من الفولاذ والخرسانة. ومع ذلك ، أدى نقص المعلومات حول أداء الخرسانة على المدى الطويل وشدة الآثار البيئية الى خلق مشاكل كبيرة. حيث تغلغل المواد الضارة أمر مزعج بشكل كبير. وان هجوم الكلوريد هو عامل رئيسي يؤثر على متانة الهياكل الخرسانية خلال فترة خدمتها. وهذا سبب محتمل في تآكل الفولاذ بالإضافة إلى تدهور وتشظي الغطاء الخرساني. يمكن لأيونات الكلوريد اختراق الخرسانة عن طريق مجموعة متنوعة من المصادر الخارجية ، بما في ذلك ملح إزالة الجليد ومياه البحر وتركيز الاملاح في المياه الجوفية. بينما تلوث المواد الداخلة بانتاج الخرسانة مثل الركام الناعم والخشن وغيرها.

إن الهدف من هذا البحث هو تطوير نموذج متكامل يراعي العديد من العوامل التي تؤثر على تغلغل الكلوريد في الهياكل الخرسانية المسلحة ، بما في ذلك العوامل الخارجية ومنها درجة الحرارة والرطوبة والعوامل الداخلية والتي تتمثل بخصائص الخرسانة مثل نسبة الماء إلى السمنت والاستبدال جزء من السمنت بمواد سمنتية بوزولانية وعرض التشققات.

تم استخدام نهج العناصر المحدودة لحل الموديل العددي وتقدير تركيز الكلوريد مع العمق والوقت $C(x,t)$ في هياكل الخرسانية المسلحة في هذا العمل بواسطة برنامج يطلق عليه تجارياً ، COMSOL Multiphysics (الإصدار الخامس).

تم استخدام العديد من البحوث السابقة للتحقق من واقعية الموديل المتكامل المقترح وتقييمه ، وعند مقارنة النتائج وجد تقارب وانحدار ارتباط لا يقل عن 83٪ وهو ضمن الحدود المقبولة و الجيدة. تم استخدام النموذج في مجموعة متنوعة من الدراسات ، بما في ذلك التغييرات في نسبة الماء إلى الأسمنت ، والرطوبة ، وعرض الشقوق ، واستخدام المواد اللاسمنتية البوزولانية ، وسيناريوهات IPCC ، 2014 التي تأخذ في الاعتبار آثار تغير المناخ.

كما تم استخدام الانشاءات الخرسانية التي تم تقديرها مع النموذج المقترح ، وبحسب التعرض البيئي ، فقد تم التطبيق على هيكلين انشائين من الخرسانة المسلحة احدهما مفترض في مدينة البصرة ومشيد عام 2020: رصيف في شط العرب بنسبة ماء - اسمنت 0.5 تعرض لمياه البحر ، وحالة أخرى. ، قنطرة صندوقية مفترض تشييدها في مدينة النجف بنسبة ماء-

أسمنت 0.4 على أساس 1.5 متر من التعرض السطحي للمياه الجوفية. وفقاً للهيئة الحكومية الدولية المعنية بتغيرات المناخ ، IPCC، 2014 ، تجاوزت درجة الحرارة 4 درجات مئوية في عام 2100 في سيناريوهين حيث تم استخدام النموذج مع تعرضات زمنية لمدة 25 و 50 عامًا. تظهر النتيجة أنه في وقت التعرض 50 عامًا ، حيث ينتشر تركيز محتوى الكلوريد مع زيادة درجة الحرارة ، وتكون فترة التعرض أطول من تراكيزات محتوى الكلوريد في وقت التعرض 25 عامًا.

تم دعم نتائج هذا البحث بأبحاث سابقة ، والتي وجدت أنه مع ارتفاع درجة الحرارة ، وعرض الشقوق ، ونسبة الماء إلى الأسمنت ، والرطوبة النسبية ، يزيد تغلغل الكلوريد في الخرسانة ، مما قد يتسبب في حدوث تآكل في قضبان حديد التسليح من ناحية أخرى. و باستخدام المواد البوزلانية يمكن أن تبطئ من تدهور الهياكل الخرسانية عن طريق زيادة مقاومة تغلغل الكلوريد.

بالنهاية يتوافق النموذج المتكامل المقترح مع نتائج ونظريات البحث الحالية ، وبالتالي يمكن استخدامه للتنبؤ باختراق الكلوريد وعمر الخدمة لهياكل الخرسانة المسلحة الأخرى .



جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل / كلية الهندسة
قسم الهندسة المدنية

التحري النظري لاختراق الكلورايد في الهياكل الخرسانية المسلحة و المعرضة
للكلورايد و التغيرات المناخية.

رسالة

مقدمة إلى كلية الهندسة في جامعة بابل كجزء من متطلبات نيل درجة الدبلوم
العالي في الهندسة/ الهندسة المدنية / المواد الانشائية

من قبل

رؤى حسن رسول اسماعيل

بإشراف

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