University of South Australia

Assessment feedback

## CIVE 4031 – Civil Engineering Project Formulation

**Assignment 3 – Research Proposal – Monday 22 September 2014 (50%)**

**Student Names:** Mengheng Ea

| Key components of this assignment | Mark | Comment by marker |
|---|---|---|
| **Introduction and Problem statement / 5** | 4.5 | Very good. |
| **Research questions & methodology /30**<br>• Are there clear, relevant and researchable research questions?<br>• Is the necessary information identified for each research question?<br>• Has the literature review been incorporated well into the proposal?<br>• Is there a discussion of alternative methodologies?<br>• Is there a justification that the selected methodology is appropriate, through reference to previous research and publications on research methods?<br>• Are the proposed research data collection methods described?<br>• Are the proposed data analysis methods described?<br>• Have costs, available equipment and technical assistance been considered? | 28 | Very good with an in depth description of the methods available and how the research will be approached |
| **Trial table of contents / 5** | 5 | Very good |
| **Schedule / 5** | 5 | Very good. |
| **General criteria / 5**<br>• clarity of expression<br>• supporting documentation for arguments<br>• correct referencing & acknowledgement<br>• logical planning and sequence<br>• use of inclusive language<br>• overall presentation, including correct grammar, spelling and punctuation | 4.5 | good clear sentence construction. |

**Summary comment** Very through and understandable.

**The Graduate qualities being assessed by this assignment are indicated by an X:**

| | | | |
|---|---|---|---|
| X | GQ1: operate effectively with and upon a body of knowledge | | GQ5: are committed to ethical action and social responsibility |
| X | GQ2: are prepared for lifelong learning | X | GQ6: communicate effectively |
| | GQ3: are effective problem solvers | X | GQ7: demonstrate an international perspective |
| X | GQ4:can work both autonomously and collaboratively | | |

**Assignment grade/mark** 47/50

**University of South Australia**

**Division of Information Technology, Engineering and the Environment**

**School of Natural and Built Environment**

# Project Formulation

# (CIVE 4031)

# Mathematical Modelling of Chloride Penetration of Mortar (BTB-20)

# <u>Research Proposal</u>

Mengheng, Ea

Due date: Monday, 26 September 2014

# Disclaimer

I declare this report to be my own work according to University academic integrity policy, unless otherwise referenced as per Harvard referencing guide UniSA.

*Mengheng Ea*

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# Nomenclature

| Symbol | Definition |
|---|---|
| C(x,t) | Chloride concentration measured at depth x and exposure time t |
| $C_i$ , $C_o$ | Initial chloride-ion concentration of the cementitious mixture prior to the submersion in the exposure solution |
| $C_s$ | Surface chloride concentration or projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis |
| D | Chloride diffusion coefficient |
| $D_o$ | Instantaneous diffusion coefficient at the reference time of $t_o$ |
| $D_{28}$ | Diffusion coefficient at 28 days |
| $D_a$ | Apparent diffusion coefficient |
| $D_{app(t)}$ | Apparent diffusion coefficient at time t |
| $D_{ins(t)}$ | Instantaneous diffusion coefficient at time t |
| $D_{ref}$ | Diffusion coefficient at reference time $t_{ref}$ |
| erf | Error function (table with values of the error function are given in standard mathematical reference books) |
| k | Time dependency factor of surface chloride concentration ($C_s$) |
| m | Time dependency factor of apparent diffusion coefficient using long term data |
| n | Time dependency factor of instantaneous diffusion coefficient using short term data |
| t | The exposure time |
| $t_1$ | Age of concrete at the beginning of immersion period |
| $t_2$ | Age of concrete at the end of immersion period |
| $t_{eff}$ | Effective age of average diffusion coefficient from test |

| | |
|---|---|
| $t_{ex}$ | Exposure time |
| $t_{ref}$ | Reference time |
| x | Depth below the exposed surface (to middle of a layer) |

# 1. Introduction

Corrosion of reinforcement has long been a costly issue leading to premature failure of concrete structures, especially in Australia as the majority of Australia's cities are located along the coastline. Every year corrosion costs Australia approximately A$13 billion (Manuel 2013). Chlorides are the primary cause of corrosion of reinforcement that leads to deterioration of the structures (Song & Shayan 1998; Robery 2005). Chlorides penetrate concrete cover and significantly increase the potential for corrosion of the steel reinforcement that eventually leads to loss of structural functionality. Therefore, it is essential to develop a reliable model for prediction of service life of concrete structures as this is necessary to provide sufficient cover in design stage. In addition it is necessary to ensure quality control in order to plan for regular maintenance to be carried out.

Through this study, it is anticipated that a reliable modelling method for chloride ingress prediction will be established, which will be used to analyse data generated in UniSA laboratory to predict its chloride penetration between 1 year and 50 years. These mortar specimens were made with cement containing different percentages of limestone mineral along with addition of varying percentages of cement kiln dust. Their results will be analysed as to reveal links between these mineral and rate at which chloride ions penetrate through mortars. Comparisons of service lives and chloride diffusion coefficients between these mortars will be done to achieve this.

## 1.1. Background

Chloride ions can be transported via three main mechanisms. One being diffusion where chloride ions are moved from high to low concentration regions under a concentration gradient, provided that adequate moisture is present. The second mechanism is called capillary absorption. This happens when chloride-containing water encounters dry surface of the concrete and this will be drawn into the concrete's porous matrix. However, the depth of penetration is generally not deep enough to reach reinforcement unless the concrete has very poor quality or shallow cover. Nevertheless, the chloride ingress is facilitated due to reduction of distance for chlorides to diffuse. Another mechanism is permeation. Chloride ions are driven into concrete matrix when hydrostatic pressure gradient is applied on one face of the concrete and this external hydraulic head can be sourced from wave actions in marine environments. Of all these mechanisms, diffusion is the principal one that can drive chlorides to the level of reinforcement, and hence will be used as a benchmark for purpose of results evaluation in this project (Stanish, Hooton & Thomas 1997). Nord NT Build 443 is believed to be the closest method in replicating a mechanism that involve diffusion only (Hamilton et al. 2007, p. 45). A study, which compares the results of chloride profiles of both mortar and concrete specimens containing 4% and 10% limestone mineral addition using Nord NT Build 443, found that there is a good correlation between the two types of specimens, thereby verifying that the test method is an appropriate testing for this research (Dedicoat, Ramji & Zeng 2013). Thus, in spite of its using mortar, the results obtained could be valid for concrete as well. The graph plotted the results of chloride profiles from this study is shown in Figure 1.

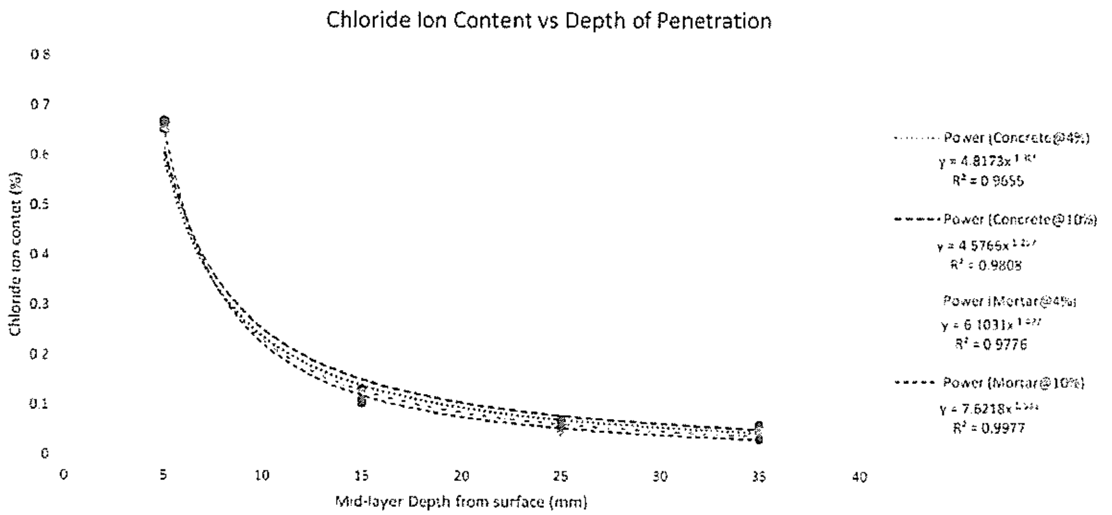


**Figure 1: Chloride profiles of concrete and mortar (Dedicoat, Ramji & Zeng, 2013)**

# 2. Problem Statement

There are a variety of models that have been developed based on Fick's second law. Nevertheless, it is noted that some of these models are incapable of accurately predicting chloride ingress in the long term and it has been suggested that this is due to lack of understanding of time-dependency of diffusion and surface chloride concentration. Due to this, it is noted that sometimes these time-dependency are not incorporated into the models altogether. Thus, it is vital to study this influence as one of the main objectives of this research is to be able to predict the long term rate of chloride penetration.

The results obtained from a suitable modelling method will be analysed in order to study the effects of mineral additions, present in the cement, will have on chloride ingress into concrete. Owing to its durability, concrete is the most used material in construction industry and cement is an essential component in making concrete. However, production of clinker, a main component of cement is concerning to the environment as it releases a large amount of carbon dioxide ($CO_2$). In fact, 0.9 tonnes of $CO_2$ is emitted for every one tonne of cement which needs 1.6 tonne of raw materials, proving this is significantly detrimental to the environment (McGrath, 2012). Consequently, in order to reduce these greenhouse gas levels, addition of mineral material such as limestone might be adopted. A small proportion of cement kiln dust (CKD), collection of waste dust from the burning of the clinker in the rotary kiln, is also suggested as mineral addition to cement as to reduce the quantity of waste material being sent to landfill. Having said that, concrete durability, especially chloride resistance, should not be compromised. Fly ash, a typical cement extender, which is shown to be beneficial in improving properties in cement such as workability, compressive strength, shrinkage reduction and in particular, its resistance to chloride ingress (Neville, 1995). Therefore, this investigation into the effect of additions of limestone and CKD as well as fly ash have on chloride penetration of concrete is being undertaken. The information will be beneficial for cement industry that running test programs to reduce greenhouse gas levels by increasing the level of mineral additions above its current level.

# 3. Research Questions

The main objective of this research investigation is to find a reliable model, which can be used to predict chloride penetration of mortar specimens in a large research programme.

The research questions that will be as well deliberated are:

- What is the effect on mortar made with cements containing increased limestone additions, cement kiln dust regarding the rate of chloride penetration?

- Would fly ash mitigate the effect of chloride ingress in concrete?
- Is the time dependency of chloride diffusion coefficient and surface chloride concentration significant at this early age of the mixes?
- Up to what percentages of limestone and cement kiln dust present in cement would provide reasonable service life?
- Which existing modelling software package(s) can be used to analyse data determined in the research?

# 4. Literature Review

Over the years, many models have been developed in order to calculate chloride concentration within concrete cover in relation to time so that service life, defined as the time until corrosion initiation, can be predicted accurately. Diffusion into a material is explained by Fick's law and thus almost all models are based on this law. However, since concrete is not a static material and has different properties from one structure to another, a simplified model that does not take these factors into account tends to underestimate or overestimate the chloride ingress. As shown across a variety of published literature, there is some discrepancy between actual chloride ingress in field data or experimental data and ones predicted by the models. This literature review was carried out in order to explore a variety of factors that can possibly cause these errors.

## 4.1. Time dependency of chloride diffusion coefficient

The most basic and simplest model developed is based on Fick's second law (Albridge, 2012a):

$$C(x,t) = C_s - (C_s - C_i)\mathrm{erf}\left(\frac{x}{\sqrt{4D}}\right) \qquad (1)$$

where

C(x, t) – chloride concentration, measured at depth x and exposure time t (% mass)

$C_s$ – projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis (% mass)

$C_i$ – initial chloride-ion concentration of the cementitious mixture prior to the submersion in the exposure solution (% mass)

x- depth below the exposed surface (to middle of a layer) (m)

D- chloride diffusion coefficient ($m^2/s$)

t – the exposure time (sec)

erf – error function (table with values of the error function are given in standard mathematical references books).

Because this is a relatively simple mathematical expression compared to other developed models, it has been widely used for practical purposes by engineers despite its oversimplified assumptions which cause the model to be too conservative. This simplified model assumes that the chloride is penetrating the cover concrete by means of only pure diffusion and that the concrete is a static, homogeneous material. As mentioned by Luguang, Wei & Jianming (2012), since concrete material is not in fact static as assumed, the simplified model fails to take into consideration of the tightening of pore structure over time which in turn make it harder for chloride to penetrate into concrete as a result of blockage of hydration materials. Therefore, it is necessary to incorporate this time-dependency of chloride diffusion coefficient in order to have a more accurate analysis.

This stated time dependency is further illustrated in a field studies of concrete exposed to marine environment in Norway carried out by Skjolsvold & Markeset (2010). In the studies, the graph where diffusion coefficients are plotted against their corresponding exposure periods of up to ten years clearly indicates that the chloride diffusion coefficient does decreases with time as also claimed by Luguang, Wei & Jianming (2012) and Tang & Gulikers (2007).

As the time-dependency of chloride diffusion coefficient has been proven by many data from various studies and experiments, it has prompted researchers to propose new mathematical expressions for the time dependency of chloride diffusion coefficients. The expression for this is (Stanish & Thomas, 2003):

$$D(t) = D_{ref}(\frac{t_{ref}}{t})^m \quad (2)$$

where

$D_{ref}$ is the diffusion coefficient at some time, $t_{ref}$

m is a variable to describe the rate of change of the diffusion coefficient.

t is the exposure period.

Chloride diffusion coefficient is determined by several test methods which can be divided into two main categories based on the duration of the test – long term and short term. The mathematical expression for diffusion coefficients obtained from both tests have the same exponential function and many researchers have used both to calculate 'm', as if they have the same meaning. It is argued to be otherwise and it is claimed that diffusion coefficient obtained from one test has different meaning to another (Luguang, Wei & Jianming, 2012). For instance, substituting time-dependency factor calculated from short term test into service life prediction model specifically developed for long term test or vice versa, leads to major errors. Thus, these have to be dealt with separately. According to Luguang & Jianming (2012, p.314), definitions of each diffusion coefficient are provided as below:

> …for long-penetration tests such as the natural immersion test or the field exposure test, because of its long immersion time, the diffusion coefficient is generally considered as an apparent diffusion coefficient or an effective diffusion coefficient ($D_{app}$), that is, the average diffusion coefficient within a certain period of time; but for the short term test, such as the rapid diffusivity tests, because of its short test time (usually continue a few hours to a day or two), the diffusion coefficient can be called the instantaneous diffusion coefficient ($D_{ins}$), that is, the diffusion coefficient of concrete at a certain time.

The time dependencies of instantaneous diffusion coefficient and apparent diffusion coefficients are presented graphically in Figure 2 and 3 respectively.

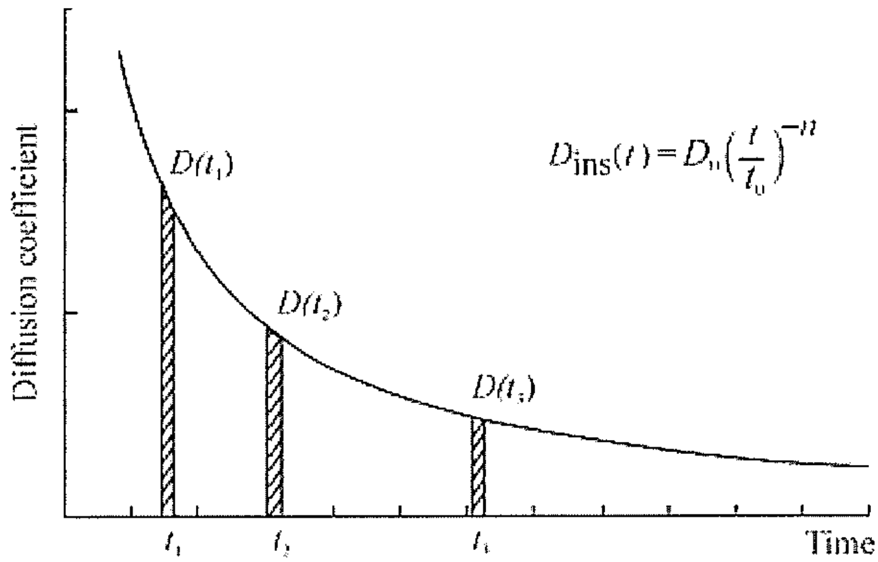


Figure 2: Time dependency of instantaneous diffusion coefficients calculated using short term penetration test (Luguang & Jianming 2012, p. 315)

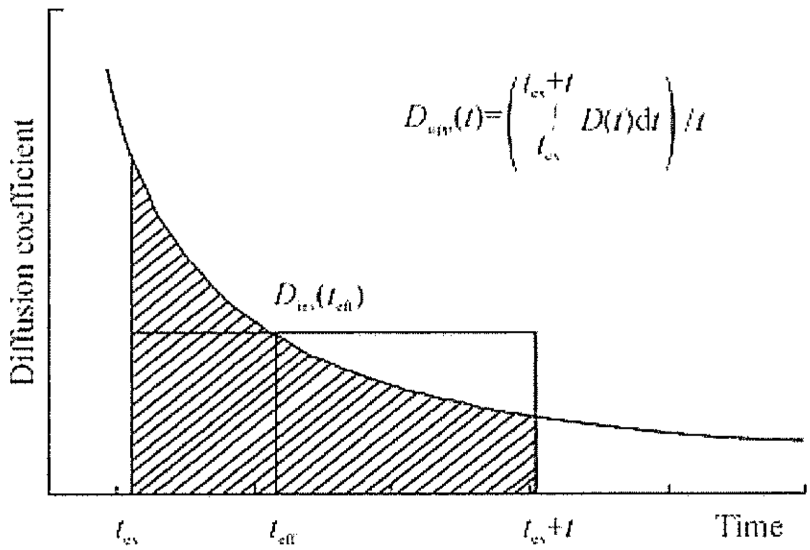


Figure 3: Apparent diffusion coefficient calculated using the long term test (Luguang & Jianming 2012, p. 316)

As noted in Nilson (cited in Luguang & Jianming 2012, p.316), after studying the relationship between the two, it is emphasised that if one of time dependencies expression is true, the other is not. A considerable number of data is needed, especially the ones from specimens exposed for a very long time in the field, in order to determine the validity of these time dependencies (Luguang, Wei & Jianming 2012).

Apart from the issue raised above, another possible error in service life prediction stems from the fact that the time-dependent diffusion coefficient is substituted directly into equation (1). However, this is argued to be mathematically incorrect due to the fact that equation (1) is derived from Fick's first law with the assumption of constant diffusion (Luguang, Wei & Jianming 2012, Tang & Gulikers 2007, Petcherdchoo 2013). Therefore, Fick's second law should be solved with new boundary conditions. Hence, two proposed service life prediction models to be used for long term penetration test and short term penetration test are shown in equation (3) & (4) and equation (5) respectively (Luguang, Wei & Jianming 2012) and these also incorporate the effect of curing period.

$$C(x,t) = C_s(1 - erf\,\frac{x}{2\sqrt{T}}) \tag{3}$$

$$T = \frac{D_O}{1-n}.[\left(1 + \frac{t'_{ex}}{t}\right)^{1-n} - (\frac{t'_{ex}}{t})^{1-n}].(\frac{t'_O}{t})^n.t \tag{4}$$

where

$D_o$ is the instantaneous diffusion coefficient at the reference time of $t_o$

n is the constant of the time dependency of instantaneous diffusion coefficient which calculated using short term test data from equation (2), but by replacing $D_{ref}$ for $D_o$ and m for n.

$t_{ex}$ is the age of concrete at the start of exposure (curing period)

t is the duration of exposure

$$C(x,t) = C_s\left[1 - erf\frac{x}{2\sqrt{D_o'(\frac{t_o}{t})^m.t}}\right] \tag{5}$$

where

$D_o$' is the apparent diffusion coefficient calculated from the long term test data from equation (2), but by replacing $D_{ref}$ for $D'_o$.

To further reinforce the importance of accurately determining time-dependency factor, in the Skjolsvold & Markeset (2010) work; a probabilistic method was utilized to numerically study the sensitivity of all relevant parameters in the model and not surprisingly the age factor is found to be a dominant one. Just by solely varying mean values of age factors, the steel reinforcement within the concrete has a high probability of fifty percent to corrode.

### 4.2. Time dependency of surface chloride concentration

Diffusion coefficient is not the only parameter that depends on time. According to Skjolsvold and Markeset (2010), Figure 3 in the article illustrates the time dependency of surface chloride concentration with exposure time. Similarly, Figure 7 and 8 within Tang and Gulikers (2007) studies also points out the same trend, notably even for concrete under submersion. The reason for this occurrence is suggested to have been caused by an increase in chloride binding capacity in relation to time. However, it is noted that there is no time-dependency of surface chloride concentration in equation (4) and (5).

In a study by Song, Lee and Ann (2008), surface chloride concentration ($C_s$) predicted by models whose $C_s$ expressions accounts for its increase over time, as in equation (6) and (7), are compared to the values of $C_s$ measured. The results showed that the models using these equations produce unrealistically low values of $C_s$ at early exposure time and thereby underestimate it. Also, the model overestimate $C_s$ at long-term exposure. A refined model results from empirical derivation of published data (equation 8), is then introduced. It includes the initial build-up of chlorides on the surface of concrete ($C_o$) and it is found that its prediction is closer to the measured data at an early age and rise to a constant value after 60 years. This is indicated in Figure 4.

$$C_s(t) = kt \qquad (6)$$

$$C_s(t) = k\sqrt{t} \qquad (7)$$

$$C_s(t) = C_o + k\ln(t) \qquad (8)$$

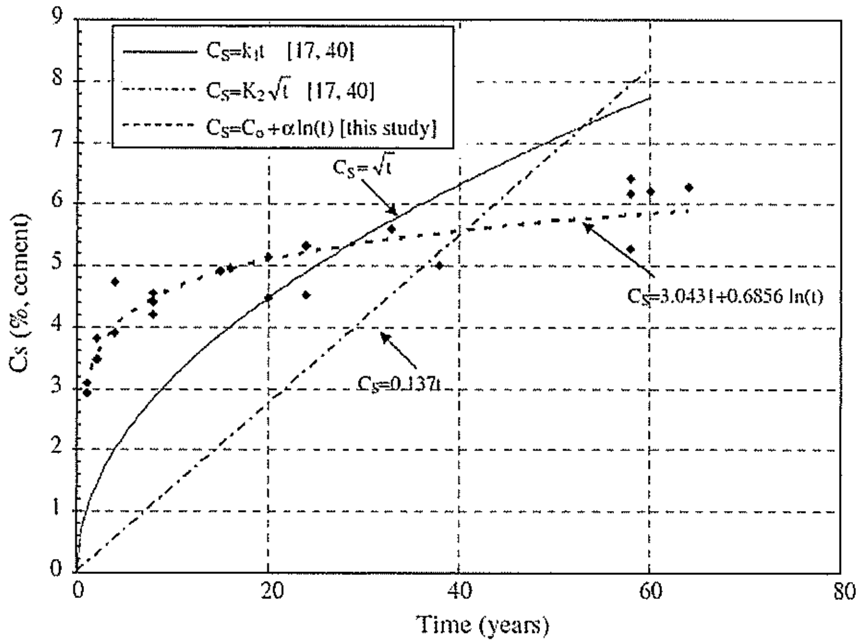


**Figure 4 Surface chloride content with time from a linear and square root build-up models, and the refined model (Song, Lee & Ann, 2008)**

In his paper, Aldridge (2012b) introduced a modelling method whose time dependency of surface chloride concentration expressed in exponential form as indicated in equation (9). The prediction by this model has a fairly well-fitted curve to experimental data produced from Nord Build 443 test at a variety of exposure times. Nonetheless, the relationships between the model prediction and experimental data are not valid after 10 years and therefore it is suggested that this is the limit of the model's reliability, otherwise it would leads to overestimation of the service life of concrete at long times. The modelling equation used is (2012b):

$$C(x) = C_o(t/t_o)^k(1 - \mathrm{erf}(\frac{x}{2\sqrt{tD_o(\frac{t}{t_o})^{-m}}})) \qquad (9)$$

Although Charlee et al. (cited in Petcherdchoo, 2013) proposed a model that takes into account of time-dependency of both diffusion coefficient and surface chloride concentration, the surface chloride concentration term in the model's equation is proven to be mathematically incompatible when compared with numerical solutions by the finite difference method (Petcherdchoo, 2013).

## 4.3. Effect of concrete properties and binder type on diffusion coefficients

Moreover, water/binder ratios also plays a fairly substantial role in affecting chloride transport within concrete. For instance, it is found that upon measurement of chloride diffusion, chloride diffusivity varies considerably across different types of water/binder ratios (Page et al. cited by Aldridge 2012a, p.2). Consequently, on top of using time-dependent diffusion coefficient and surface chloride concentration, Life-365 model also relate its diffusion coefficient to water binder ratio (Maheswaran & Sanjayan 2004, p.6). This model still has not considered all effects as it is widely known that due to the way the pore structure of different concrete mix proportion is formed differently, the effect of binder type is also attributed to time-dependency of chloride diffusion (Song, Lee & Ann 2008, p.115). For example, due to the nature of fine particle size distribution along with dense matrix in concrete containing pulverized fuel ash (PFA) and ground granulated blast-furnace slag (GGBS), the transportation of chlorides into this material is comparatively slower. Chloride diffusion is found to vary by an order of magnitude in concrete with different cement types (Hansson et al. cited by Aldridge 2012a, p.3). According to statements of the preceding two sources, it is obvious that the effect of binder type also accounts for the variation of chloride diffusion in concrete. Thus, it is important to not ignore this effect as shown in Tang and Gulikers (2007): when actual ingress profiles are compared with chloride profiles obtained from a model not accounting for binder replacement, although it can relatively predict the ingress well in Portland cement concrete, it leads to a considerable underestimation of chloride ingress in concrete containing fly ash.

In eliminating possible errors in the oversimplified model discussed so far that can cause inaccuracies in service life prediction, Petcherdchoo (2013) developed a model:

$$C(x,t) = C_o\left[erfc\left(\frac{x}{2\sqrt{D_a t}}\right)\right] + k \times \sqrt{t}\,[e^{-\frac{x^2}{4D_a t}} - \left(\frac{x\sqrt{\pi}}{2\sqrt{D_a t}}\right) erfc(\frac{x}{2\sqrt{D_a t}})] \quad (10)$$

$$D_a = \frac{D_{28}}{1-m}\left[\left(1+\frac{28}{365t}\right)^{1-m} - \left(\frac{28}{365t}\right)^{1-m}\right].\left(\frac{28}{365t}\right)^m \quad (11)$$

where

$D_{28}$ is diffusion coefficients at 28 days ($mm^2$/year).

k is a constant related to the rate of increase of surface chloride per square root of the exposure time.

x and t are the distance from concrete surface (mm), and the time after exposure (years), respectively.

m is age factor.

It is noted that this model requires two sets of measured data at two different times.

Nevertheless, Tang (2008) argues that empirical models based on Fick's second law in general are incorrect in the sense that the total chloride is taken as driving potential while in fact it is the free chloride and thus a physical and chemical based model is more appropriate, for instance, ClinConc model (Tang 2008). Plus, this model also considers the non-linearity of chloride binding capacity unlike other empirical models. Despite an attempt to modify the original ClinConc model to be more engineer-friendly with less sophiscated numerical evaluation, there are still a lot of parameters to be determined, in particular, chloride binding constants have to be determined from chloride binding isotherms. It should also be noted that data from short term test is required for this model.

Elsewhere, validation of another model using short term test data, DuraCrete model, results in a conclusion that it can predict chloride ingress fairly well provided that diffusion coefficient at half a year is used as opposed to 28 days because with the latter, the choride ingress is underestimated (Tang & Lindvall 2013).

## 4.4. Existing modelling software packages

Over the years, although Fick's-law-based models have been continuously modified and developed to eliminate the assumptions present in model as shown in Equation (1), they still inevitably fail to consider several real-world factors which vary from one concrete structure to another such as concrete mixture proportions, different types of reinforcing bars and their coating materials. Furthermore, since these models use basic spreadsheet, they lack~~s~~ the flexibility in updating material properties and boundary conditions using tedious iterative procedure. On the other hand, according to Bentz et al. (2014), models developed using powerful, advanced computer program are more flexible and accurate, because they are capable of solving the differential form of Fick's first law using finite-element analysis and permits implementation of real-world considerations. In the paper, an overview of existing modelling software packages were given. Firstly, Life-365 is able to model up to two dimensional chloride exposure and gives the options of selecting different materials (reinforcing bars and their corresponding coating materials), concrete mixture proportions. Another concrete-specific model mentioned was STADIUM 2.99. Not only is this model ~~be~~ able to evaluate the effect of corrosion-protection measures (sealers, membranes and thick overlays), for different types of steel reinforcements, it holds a wide-range of databases of corresponding corrosion thresholds plus exposure conditions. Lastly, a generalized simulation and modelling package called the COMSOL Multiphysics is also able to predict concrete service life by linking its several modules such as transport/reaction module, mechanical/thermal response and corrosion modules.

## 4.5. Summary of literature review

The literature review discussed above has provided explanations as to why some of the existing models inaccurately predict the actual chloride ingress. Through various experimental studies and sensitivity analysis, even though time dependency expressions of diffusion coefficient and surface chloride concentration has to be accommodated for in the model to account for their effects, this should be integrated with correct boundary conditions from Fick's first law to ensure its mathematical compatibility. Otherwise, this will lead to errors.

Moreover, the literature has cleared confusion between meanings behind apparent and instantaneous diffusion coefficients. As chloride penetration test methods are predominantly classified into two main types based on duration of the test – short term and long term, choosing test data to be used in specific model has to be exercised carefully to avoid errors.

Furthermore, not only should a model contain an expression of surface chloride concentration as time-dependent, but initial build-up of chlorides on the surface of concrete ($C_o$) and non-linearity expression of time should be accounted for, because time-dependent surface chloride concentration ($C_s$) is believed to be caused by chloride binding capacity and by nature this is not linear.

Although it is virtually agreed that D can be expressed in exponential form, there are a variety of model expressions for $C_s$ and this might be due to lack of understanding of its physical process.

Last but not least, the effect of concrete properties such as curing, water/binder ratio and binder type should not be ignored either as it can significantly affect the accuracies of the model's prediction.

The models presented by equations (9) and (10) & (11) seem to be promising models to be used in this research investigation for long term test while DuraCrete model, on the other hand, is potentially a fairly good model to be used for short term test.

# 5. Research Methodology

This section detailed the research methodology that will be used to complete the objectives and answer research questions set out in Section 3.

Three potential models discussed in the literature~~s~~ ~~and~~ are outlined below and will be utilised to analyse the published data (Section 5.5) in order to validate their reliability. The unknown regression parameters which are chloride diffusion coefficient at reference time ($D_o$ or $D_{28}$ if reference time is 28 days), initial surface chloride concentration ($C_o$) and their time-dependent factors (m and k respectively) are found using sum of square differences between the chloride profile from the regression analysis by experimental or field data and that by developed model. This common method of deriving the unknown parameters by regression analysis is shared among the models outlined and this can be done by just using readily available spreadsheet application, namely Excel. Any iterations required can be performed by Excel solver routine. The chloride profiles are created by plotting the chloride contents against their corresponding depths from the surface of the concrete.

Once these parameters are found, they are substituted back into original modelling equations along with exposure times and depths to get its corresponding chloride content. These can then be compared to the measured ones to determine the models' accuracies in their predictions. It is anticipated that among the three models, one or two better models are capable of reasonably predicting actual chloride content. These are then chosen to analyse the data produced in UniSA laboratory by Nord NT Build 443 test.

As has been discussed in the foregoing section, since the models chosen account for both time dependency of chloride diffusion coefficient and surface chloride concentration, at least two sets of data at different exposure times are needed for a successful regression analysis. Experimental data from specimens exposed for 35 days and 140 days will be available and thus are viable to be analysed by the models.

As to evaluating the significance of time dependency of chloride diffusion coefficient (D) and surface chloride concentration ($C_s$) at early age of the mixes, an observation of these values against time would provide the answers to this. Should the time dependency factors (m or n) of any mixes is made zero and still provide a good fit to actual chloride profiles, a conclusion could be drawn regarding how at this stage, D and $C_s$ are not particularly dependent on time.

To predict the service life between 1 year and 50 years, values of critical chloride content and cover depth along with found parameters from regression analysis will be used to substitute into modelling equations to calculate time (t). This is the time before corrosion of steel reinforcement begins or in short is the service life. The critical chloride content and cover depth generally used in current practice in Australia will be modelled. As specified in AS 1379 (1998), critical chloride content that would take to initiate steel reinforcement corrosion is based on 0.8 $kg/m^3$ of concrete. With a typical density of concrete $2350 kg/m^3$, this equals to 0.034% chloride and for a typical density of mortar at $2200 kg/m^3$, this equals 0.036%. Finally, a target of 0.034% is conservatively chosen to be used in this research. On the other hand, according to AS 3600 (2009), concrete members situated in coastal areas are considered to be in the B2 exposure classification according to Table 4.3 of the standard. With concrete strength of 40 MPa commonly used in durable concrete structures, the required cover is 45 mm.

Lastly, the three modelling software packages mentioned in the literature review, which are Life-365, STADIUM 2.99 and COMSOL Multiphysics, will be investigated regarding their feasibility to be used in the research programme. Their user's manuals and online files will be consulted in order to determine their capabilities and limitations as well as what input data is required and whether these can be generated from Nord NT Build 443 test or others. However, due to time constraint of this project, none of them will be used to analyse the data.

## 5.1. Model 1

As discussed in literature review, both chloride diffusion coefficient and surface chloride concentration vary with time. Thus this model is selected as it not only takes these into account but also is proven to be a mathematically compatible chloride transport model. This is because it is solved from Fick's first law with correct boundary conditions. Besides, in this model, $\sqrt{t}$ is chosen instead of a linear function due to its capability in expressing the rise of nonlinear surface chloride. Besides, $C_o$ is also included in the model as it is known that as soon as concrete is exposed to marine environment, chlorides are bounded onto surface of concrete. The modelling equations are (Petcherdchoo 2013):

$$C(x,t) = C_o\left[erfc\left(\frac{x}{2\sqrt{D_a t}}\right)\right] + k \times \sqrt{t}\,[e^{-\frac{x^2}{4D_a t}} - \left(\frac{x\sqrt{\pi}}{2\sqrt{D_a t}}\right) erfc(\frac{x}{2\sqrt{D_a t}})] \quad (10)$$

$$D_a = \frac{D_{28}}{1-m}\left[\left(1+\frac{28}{365t}\right)^{1-m} - \left(\frac{28}{365t}\right)^{1-m}\right].(\frac{28}{365t})^{m} \quad (11)$$

$$C_s(t) = C_o + k\sqrt{t} \quad (12)$$

where k denotes time dependency factor of $C_s$.

Set out below are the steps used in regression analysis to find unknown parameters; several tables illustrated provide an explanation when taking mixes with different percentages of limestone as an example:

1. $m = 2.5*(w/c) - 0.6$ (Mangat & Molloy 1994)
2. $D_{28}$ , $C_o$ and k found from regression analysis for different exposure time and different percentages of mineral addition
3. To find these three regression parameters, the sum of the squared differences between the chloride profile from the regression analysis by published or experimental data and that by the developed model is minimized by adjusting the regression parameters.
4. After first regression analysis, k is expected to be found as 0. Time dependent effect vanishes because of analysis performed year by year. To avoid this, substitute $C_o$ from initial results into $C_s$ in equation (12) in addition to matching with their exposure time.
5. Plot $C_s$ against $\sqrt{t}$ , insert a trend line and then $C_o$ can be found from intercept of the trend line on y axis.
6. Set $C_o$ found, perform regression analysis again and adjusted results will be obtained.

**Table 1: Regression parameters for 4% Limestone**

| Parameters | Initial Results | | Adjusted Results | |
|---|---|---|---|---|
| | 35 days exp. | 114 days exp | 35 days exp | 114 days exp |
| $D_{28}$ | | | | |
| m | | | | |
| $C_o$ | | | | |
| k | | | | |

7. Repeat this same procedure for concrete containing varying percentages of mineral additions (e.g. 4%, 10%, 15%)

8. Average diffusion coefficients at 28 days over various exposure time (e.g. 35 days, 114 days) then plot them against amount of limestone (%LS)

**Table 2: Values of $D_{28}$ from the adjusted results**

| Mix No | $D_{28}$ | | |
|---|---|---|---|
| | 35 days exp. | 114 days exp. | Average (35 days to 114 days) |
| GP 4 | | | |
| GP 10 | | | |
| GP 10+5 | | | |

9. Insert trend line, get an equation representing $D_{28}$ for different %LS. From this trend line equation $D_{28}$ can be expressed in terms of %LS. (Note: adjust trend line equation accordingly (make it linear or non-linear, whichever fits with experimental data best)
10. Average $C_o$ and k over exposure time and %LS

**Table 3: Value of $C_o$ from the adjusted results**

| Mix no. | | | | |
|---|---|---|---|---|
| | 35 days exp. | 114 days exp | Average (35-114 days) | Average (4 – 20%LS) |
| GP 4 | | | | |
| GP 10 | | | | |
| GP 20 | | | | |

Table 4: Value of k from the adjusted results

| Mix no. | | | | |
|---|---|---|---|---|
| | 35 days exp. | 114 days exp | Average (35-114 days) | Average (4 – 20%LS) |
| GP 4 | | | | |
| GP 10 | | | | |
| GP 20 | | | | |

11. Plot $\log C_o$ against %LS and do the same plot for k and then add trend line to get the equation representing their relationships in terms of %LS and then substitute into equation (12)

### 5.2. Model 2

By using apparent diffusion coefficient at effective age ($t_{eff}$) rather than average diffusion coefficient, this model proves to produce more realistic results because according to (Stanish & Thomas 2003), when the latter is used in service life prediction, it is implicitly assumed that the age of concrete first exposed to chloride environment is the same during testing and in service. As a result, by using apparent diffusion coefficient, it is thought to depict a more realistic scenarios where conditions in service is not always similar to conditions during testing. However, since this model did not originally include time dependency of surface chloride concentration, it was modified by replacing its constant expression $C_o$ by $C_o + k\ln(t)$ as shown in equation (8) in literature review. Below sets out the steps used in regression analysis to find unknown parameters

1. For each exposure period (35 days and 114 days), calculate average diffusion coefficients ($D_{avg}$) which is the result of fitting the chloride profile to equation (13):
   $C(x,t) = (C_o + k\ln t)\mathrm{erfc}(\frac{x}{\sqrt{4Dt}})$ (13)
2. Assume a value for time dependency factor of chloride diffusion coefficient (m)

3. For each exposure period (35 days and 140 days), calculate effective age from equation (14):

$$t_{eff} = \begin{cases} \left[\frac{(1-m)(t_2-t_1}{t_2^{1-m}-t_1^{1-m}}\right]^{1/m}, m \neq 0, 1 \\ \\ \frac{t_2-t_1}{\ln(\frac{t_2}{t_1})}, m = 1 \end{cases} \quad (14)$$

4. Determine the logarithms of ($D_{av}$) and the effective ages from step 2
5. Determine the value of m from the negative slope of the line of best fit using the logs of the effective ages as the x-values, or in other word, negative slope $\log D_{avg}$ vs $\log t_{eff}$ This is based on equation:

$$D_{app} = D_{ref}(\frac{t_{ref}}{t_{eff}})^m \quad (15)$$

6. Repeat step 3 through 5 with the new value of m. When the m value determined from step 5 is equal to the m value used in step 2, the value of m is established for the concrete.
7. The intercept of the line of best fit will be the log of the 1-day diffusion coefficient (if age is given in days). Correct to the reference age using equation (16)

$$D(t) = D_{ref}(\frac{t_{ref}}{t})^m \quad (16)$$

and the value of m just determined.
8. The procedure to determine $C_o$ and k is similar to model 1.

### 5.3. Model 3

Similarly, this model is based on Fick's second law. The main difference here is its time dependency of surface chloride concentration is expressed in exponential form. It is observed that there were not any models that use this expression and hence it is worth finding out if this is the more accurate way of describing change in surface chloride concentration.

The modelling equation is as follows (Aldridge, 2012b):

$$C(x) = C_o(t/t_o)^k(1 - \mathrm{erf}(\frac{x}{2\sqrt{tD_o(\frac{t}{t_o})^{-m}}})) \quad (17)$$

m and $D_o$ are found from regressions analysis on the plots of $\ln(D/D_{28})$ against $\ln(t/t_o)$, while k and $C_o$ are found from regression analysis on the plots of $\ln(C_s/C_{28})$ against $\ln(t/t_o)$.

Regression of these plots can be done on an Excel spreadsheet and their corresponding equation are shown in equation (18) and (19).

$$Ln(D/D_{28}) = slope_D Ln(t/t_o) + Intercept_d \quad (18)$$

$$Ln(C/C_{28}) = slope_k ln(t/t_o) + Intercept_c \quad (19)$$

$$m = -slope_D,\ k = slope_s,\ D_o = D_{28}*exp(Intercept_D)\ \&\ C_o = C_{28}*exp(Intercept_c)$$

## 5.4. Alternative Model

An alternative model, an engineering expression of the ClinConc model modified by Tang (2008), was considered. Among all models discussed in the literature review, this model is the only one that is based on physical and chemical process involve in diffusion of chloride into concrete. Furthermore, in the same study in which the model is modified, good correlations are found between the time dependent factors for chloride binding and for diffusion coefficient, as well as between the diffusion coefficient measured in the laboratory and the apparent one. However, it is decided this is not feasible because there are a number of unknown parameters that have to be determined from other tests, specifically, chloride binding isotherms.

## 5.5. Published Data

The published data that will be analysed by the three models are shown in Table (5) (Thomas & Bamforth 1999). These data are from fifteen cast reinforced concrete blocks that were exposed in the splash zone on the sea front at Folkestone on the southeast coast of England. This consists of three different mixes: concrete with Portland cement only, concrete with 30% fly ash (P/PFA) and 70% slag (P/GBS) as partial replacement for the Portland cement.

Table 5: Published Data (Thomas & Bamforth 1999)

| Mix | Depth (mm) | Chloride content (percent mass of concrete) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 6 month | 1 year | 2 years | 3 years | 6 years | 8 years |
| PC | 0-10 | 0.267 | 0.493 | 0.313 | 0.370 | 0.257 | 0.288 |
| | 10-20 | 0.140 | 0.193 | 0.273 | 0.273 | 0.237 | 0.264 |
| | 20-30 | 0.050 | 0.043 | 0.143 | 0.190 | 0.197 | 0.203 |
| | 30-40 | 0.010 | 0.017 | 0.093 | 0.117 | 0.153 | 0.183 |
| | 40-50 | 0.000 | 0.000 | 0.053 | 0.073 | 0.133 | 0.159 |
| P/PFA | 0-10 | 0.280 | 0.427 | 0.333 | 0.383 | 0.367 | 0.419 |
| | 10-20 | 0.087 | 0.097 | 0.160 | 0.173 | 0.193 | 0.308 |
| | 20-30 | 0.007 | 0.010 | 0.037 | 0.013 | 0.010 | 0.057 |
| | 30-40 | 0.000 | 0.023 | 0.010 | 0.010 | 0.010 | 0.012 |
| | 40-50 | 0.000 | 0.000 | 0.010 | 0.010 | 0.010 | 0.012 |
| P/GBS | 0-10 | 0.437 | 0.493 | 0.340 | 0.387 | 0.363 | 0.381 |
| | 10-20 | 0.173 | 0.140 | 0.173 | 0.153 | 0.227 | 0.216 |
| | 20-30 | 0.077 | 0.090 | 0.023 | 0.027 | 0.067 | 0.068 |
| | 30-40 | 0.027 | 0.073 | 0.010 | 0.013 | 0.040 | 0.035 |
| | 40-50 | 0.000 | 0.000 | 0.013 | 0.010 | 0.030 | 0.035 |

## 5.6. Experimental Data from Nord NT Build 443

The data that will be used is from work carried out in 2013 by Jogi et al. (2013) and more data is to be determined during the course of this semester.

Table 6: 2013 mix details (Benn B.T., Baweja D. and Mills J.E. 2014)

make column wider

| Mix | Nominal limestone content | CKD content | Sand/binder ~~r~~ ratio | Water/binder ratio |
|---|---|---|---|---|
| Cement only | 4% | Zero, 2%, 5% | 1.99 | 0.40 |
| | 10% | " | 1.99 | 0.40 |
| | 15% | " | 1.99 | 0.40 |
| Cement with 20% FA | 4% | " | 1.93 | 0.40 |
| | 10% | " | 1.93 | 0.40 |
| | 15% | " | 1.93 | 0.40 |
| Cement with 30% FA | 4% | " | 1.89 | 0.40 |
| | 10% | " | 1.89 | 0.40 |
| | 15% | " | 1.89 | 0.40 |

Table 7: 2014 mix details

| Mix | Nominal limestone content | CKD content | Sand/binde r ratio | Water/binder ratio |
|---|---|---|---|---|
| Cement only | 4% | Zero, 2%, 5% | 1.99 | 0.40 |
| | 10% | " | 1.99 | 0.40 |
| | 15% | " | 1.99 | 0.40 |
| Cement with 20% FA | 4% | " | 1.93 | 0.40 |
| | 10% | " | 1.93 | 0.40 |
| | 15% | " | 1.93 | 0.40 |
| Cement with 40% FA | 4% | " | 1.89 | 0.40 |
| | 10% | " | 1.89 | 0.40 |
| | 15% | " | 1.89 | 0.40 |
| Cement with 30% GGBS | 4% | " | 1.93 | 0.40 |
| | 10% | " | 1.93 | 0.40 |
| | 15% | " | 1.93 | 0.40 |
| Cement with 60% GGBS | 4% | " | 1.89 | 0.40 |
| | 10% | " | 1.89 | 0.40 |
| | 15% | " | 1.89 | 0.40 |

# 6. Proposed Schedule of Work and Resources Required

A detailed project schedule is shown in Appendix A. Table 7 below is comprised of a list of key dates during the period of the research.

Table 7: Key Dates of Project

| Key Dates | Descriptions |
|---|---|
| 29 September 2014 | Start of Proposed Research Work |
| 29 September 2014 to 26 October 2014 | Investigation and Modelling Stage |
| 20 October 2014 onwards | Start Drafting Report |
| 20 October 2014 | Plan and Develop Poster |
| 23 October 2014 | Submit Abstract of Poster |
| 26 October 2014 | Completion of Investigation and Modelling Stage |
| 27 October 2014 | First Draft Submission to Supervisors and Amendments<br><br>Draft Poster to Supervisors and Course Coordinator |
| 03 November 2014 | Final Submission of Poster |
| 06 November 2014 | Poster Presentation at Festival of Innovation |
| 10 November 2014 | Final Draft Submission to Supervisor and Amendments |
| 17 November 2014 | Final Submission of Report |

The university's IT facilities should prove adequate for the majority of the research and analysis required by this study.

# 7. Proposed Table of Contents for Final Report

The proposed table of contents for the final project report is as follows:

1. Executive Summary
2. Introduction
   2.1. Research Objectives
   2.2. Problem Statements
3. Literature Review
   3.1. Time dependency of chloride diffusion coefficient
   3.2. Time dependency of surface chloride concentration
   3.3. Effect of concrete properties and binder type on diffusion coefficients
   3.4. Existing Modelling Software Packages
   3.5. Summary of literature review
4. Research Methodology
   4.1. Model 1
   4.2. Model 2
   4.3. Model 3
   4.4. Alternative Model
   4.5. Published Data
   4.6. Experimental Data from Nord NT Build 443
5. Analysis of Results
   5.1. Published Data Results
   5.2. Research Data Results
   5.3. Modelling Software Packages
6. Discussion and Conclusion
   6.1. Further research recommendations
7. References
8. Appendices

# 8. References

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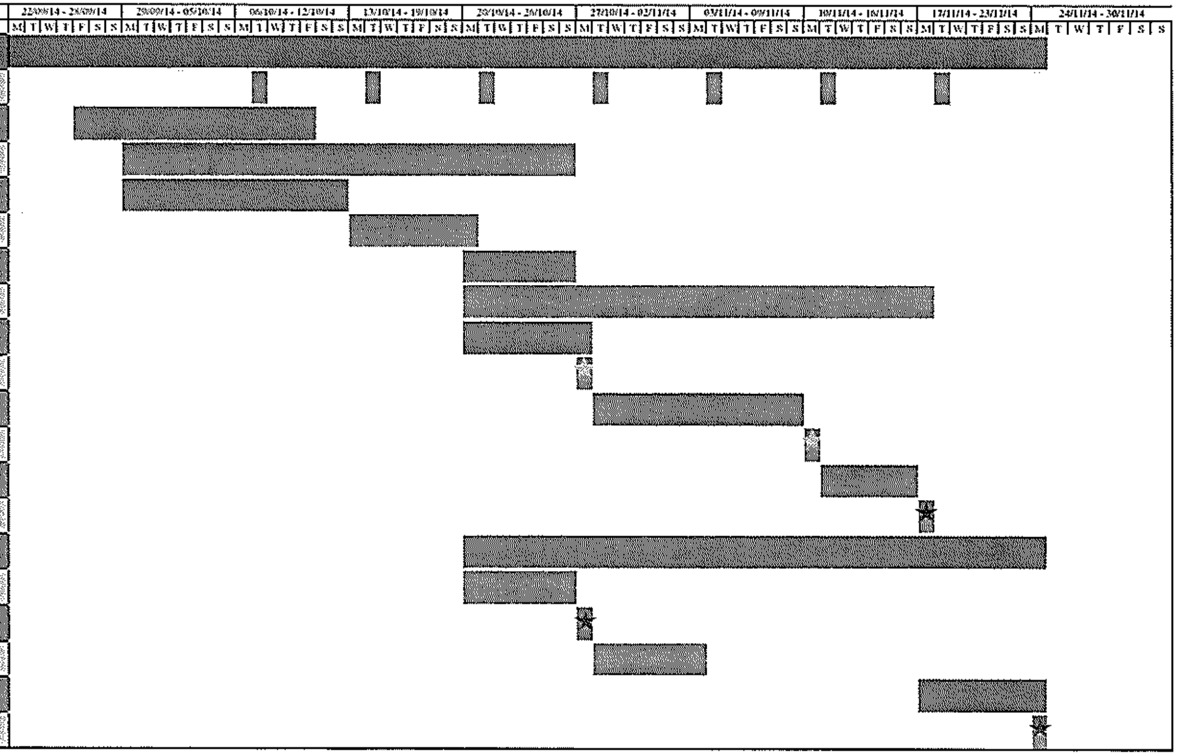
# 9. Appendices

## Appendix A: Gantt chart

| Tasks | Start | End | Working Days |
|---|---|---|---|
| **Honours Project** | 23-Sep-14 | 24-Nov-14 | 45 |
| Supervisor Meetings | 07-Oct-14 | 18-Nov-14 | 7 |
| Data Collection and Compilation | 26-Sep-14 | 10-Oct-14 | 20 |
| **Investigation and Modelling Stage** | 29-Sep-14 | 26-Oct-14 | 10 |
| Data Analysis of Published Data | 29-Sep-14 | 12-Oct-14 | 10 |
| Data Analysis of Research Data | 13-Oct-14 | 20-Oct-14 | 6 |
| Existing Modelling Software Packages | 20-Oct-14 | 26-Oct-14 | 5 |
| **Final Report Stage** | 20-Oct-14 | 17-Nov-14 | 21 |
| Draft Report Writing | 20-Oct-14 | 27-Oct-14 | 6 |
| First Draft Submission to Supervisors | 27-Oct-14 | 27-Oct-14 | 1 |
| Draft Report Amendments | 28-Oct-14 | 09-Nov-14 | 9 |
| Final Draft Submission to Supervisors | 10-Nov-14 | 10-Nov-14 | 1 |
| Final Draft Report Amendments | 11-Nov-14 | 16-Nov-14 | 4 |
| Final Submission to Course Coordinator | 17-Nov-14 | 17-Nov-14 | 1 |
| **Poster Presentation** | 20-Oct-14 | 24-Nov-14 | 26 |
| Planning and Developing Poster | 20-Oct-14 | 26-Oct-14 | 5 |
| Draft Poster Submission to Course Coordinator | 27-Oct-14 | 27-Oct-14 | 1 |
| Amendments and Final Poster Submission to Course Coordinator | 28-Oct-14 | 03-Nov-14 | 5 |
| Preparation of Poster Presentation | 17-Nov-14 | 24-Nov-14 | 6 |
| Seminar and Poster Presentation | 24-Nov-14 | 24-Nov-14 | 1 |




Legends: ☆ Deliverables to Supervisor ★ Deliverables to Course Coordinator

# University of South Australia

## Division of Information Technology, Engineering and the Environment

## School of Natural and Builts Environment

# Project Formulation (CIVE 4031)

# Mathematical Modelling of Chloride Penetration of Mortar (BTB-20)

# PRELIMINARY REPORT

Mengheng, Ea

Due date: Monday, 11 August 2014

# Disclaimer

I declare this report to be my own work according to University academic integrity policy, unless otherwise referenced as per Harvard referencing guide UniSA.

*Mengheng Ea*

# Contents

# Introduction

Corrosion of reinforcement has long been a costly issue leading to premature failure of concrete structures, especially in Australia as majority of Australia's cities are located along the coastline. Every year corrosion costs Australia approximately A$13 billion (Manuel 2013). Chlorides are the primary cause of corrosion of reinforcement that leads to deterioration of the structures (Song & Shayan 1998; Robery 2005). Chlorides penetrates concrete cover and significantly increase the potential for corrosion of the steel reinforcement that eventually leads to loss of structures' functionality. Therefore, it is very essential to develop a reliable model for prediction of service life of concrete structures as this is necessary to provide sufficient cover in design stage. In addition it is necessary to ensure quality control in order to plan for regular maintenance to be carried out.

## Background

Chloride ions can be transported via three main mechanisms. One being diffusion where chloride ions are moved from high to low concentration regions under a concentration gradient provided that adequate moisture is present. Second mechanism is called capillary absorption. This happens when chloride-containing water encounters dry surface of the concrete and this will be drawn into the concrete's porous matrix. However, the depth of penetration is generally not deep enough to reach reinforcement unless the concrete has very poor quality or shallow cover. Nevertheless, the chloride ingress is facilitated due to reduction of distance for chlorides to diffuse. Another mechanism is permeation. Chloride ions are driven into concrete matrix when hydrostatic pressure gradient is applied on one face of the concrete and this external hydraulic head can be sourced from wave actions in marine environments. Among all these mechanisms, diffusion is the principal one that can drive chlorides to the level of reinforcement, and hence will be used as a benchmark for purpose of results evaluation in this project (Stanish, Hooton & Thomas 1997). Nord NT 443 is believed to be the closest method in replicating a mechanism that involve diffusion only (Hamilton et al. 2007, p. 45).

### Objectives of investigations

The aim of this project is to establish a reliable modelling method for chloride ingress prediction. Suitable scientific or empirical modelling methods will be used to analyse data obtained from two sets of test results. One set of data is from 27 specimens made in 2013 while another is from 45 specimens made in May 2014. The model should be able to predict chloride penetration from the data obtained from the former specimens for between 3 months and 50 years while the latter data will be used in the model to ascertain the model's accuracy. According to initial research, it is found that most models seemed to be based on Fick's second law (Albridge, L & Collins, F, 2012):

$$C(x,t) = C_s - (C_s - C_i)\mathrm{erf}\left(\frac{x}{\sqrt{4D}}\right)$$

Where

$C(x, t)$ – chloride concentration, measured at depth x and exposure time t (% mass)

$C_s$ – projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis (% mass)

$C_i$ – initial chloride-ion concentration of the cementitious mixture prior to the submersion in the exposure solution (% mass)

x- depth below the exposed surface (to middle of a layer) (m)

D- chloride diffusion coefficient ($m^2/s$)

t – the exposure time (sec)

erf – error function (table with values of the error function are given in standard mathematical references books).

Despite this being the more popular principle used to develop existing models, models based on other principles will also be considered and modification of certain models might be made if necessary to take into account the influence of various cementitious materials and concrete properties such as curing time. It is very significant to seek the most "reliable" modelling method as it will be used as part of a large research programme.

# Research Plan

The entire project will comprise four main stages:

- Preliminary Report
- Literature Review
- Research Proposal
- Research Investigation

Based on these stages, the entire project is broken down into several actions and spread out across the entire semester to ensure its completion and the schedule is summarised in the GANTT chart attached in Appendix A.

## Preliminary report

The preliminary report stage is concerned with familiarising, the researcher, with the investigation topic, to organise a proposed plan to tackle any initial issues found and to ensure that the project can be completed in the set timeframe. From preliminary research, there are a variety of models that has been developed based on Fick's second law. Nevertheless, it is noted that these models are incapable of accurately predicting chloride ingress in the long term and it has been suggested that this is due to lack of understanding of time-dependency of diffusion and surface chloride concentration. Due to this, it is noted that sometimes these time-dependency are not incorporated into the models altogether. Thus, it is vital to study this influence as one of the main objectives of this research is to be able to predict the long term rate of chloride penetration.

### Literature review

The preliminary report is followed by literature review where a critical review of published work relevant to the topic such as journals, books and research papers will be carried out. Its main aim is to formulate research questions based on the preliminary report as well as to discuss at length any other findings. As noted earlier, it is important to conduct an extensive literature review on the mathematical theories of diffusion with a focus on time-dependency as this may be the answer to the underlying problem.

In addition to this, it is also beneficial to take into account of a range of other variables that can influence diffusion of chlorides as well. This will be done by reviewing literature related to concrete properties and the cementitious materials to establish understandings of their significance and impact in this phenomenon.

As these could play an important roles in predicting chloride ingress, it is will also be worthwhile considering models that are not just based on Fick's laws. Any already generated data that demonstrates interrelation between depths of penetration and diffusion in concrete properties would help to further extend our knowledge base on chloride ingress.

This has brought us into an important aspect of modelling which is to test the validity of the model. In this phase, a review of different statistical model validation method, for example, sensitivity analysis of model parameters, will be investigated and the most viable method will be chosen to use in the investigation phase to validate the existing models in order to select a reliable one.

### Research proposal

A more detailed research proposal related to the preliminary report and literature review, which might need some adjustments after feedback, will be submitted to gain approval from the supervisor for approval

### Research Investigation

The research investigation phase is divided into two main parts, with one part devoted to laboratory work in generating the results from May 2014 specimens and another devoted to modelling analysis.

The Nord Test method NT Build 443- Concrete, Hardened: accelerated chloride penetration will be used to obtain results from 45 specimens made in May 2014. This same test was also used in acquiring results from 27 specimens made in 2013.

In order to do modelling analysis, results generated from laboratory work this year and last year as well as any relevant existing data from literature review will be used. As mentioned previously, in addition to literature review on concrete properties' influence on chloride ingress, analysis of the results obtained from specimens made last year will further provide useful insight into the relationship between depths of penetration and concrete properties. If this proves to be significant, modification of existing models to reflect this may be necessary.

Based on the data from 27 tests carried out in 2013, these modified models will then be used to predict the rate of chloride penetration for between 3 months to 50 years. These will be further verified by tested for accuracy using the results obtained from 45 specimens made in May 2014, and validated by the chosen statistical validation method from literature review. Moreover, as these two sets of specimens are made in the same controlled conditions but with different proportion of mineral additions, comparison of these two sets of analysed data will provide a key knowledge in understanding the impact of concrete minerals, for instance, fineness of cement paste. A conclusion might be drawn as to how different minerals affecting diffusion of chlorides in concrete. Once a reliable model has been found, a neat and user-friendly excel workbook will be developed for this model using Visual Basic Application (VBA) code and other features of excel to provide easy access and navigation for subsequent research.

## Deliverables

The expected outcome of this project will be as follows:

- Preliminary report: provide basic understanding of the topic and proposed conduction plan of this research project.
- Literature review:
    - A more in-depth knowledge of diffusion mechanism and principles behind Fick's laws.
    - A better understanding of concrete properties and cementitious materials
    - Two models from literatures.
    - A statistical model validation method chosen.
- Research investigation phase:

- Results of chloride penetration from 45 specimens made in May 2014.
- Data analysis of the two models from literature review to produce the most reliable model.
- After validation of model, conclusion can be drawn regarding model limitations and recommendations of future work to be carried out to improve current model.
- Produce a model in excel workbook format that can be used for future research

These planned deliverables and their timeframe summarised in the GANTT chart and are subject to change throughout the course of this project depending on the success of each tasks set and available time.

# Reference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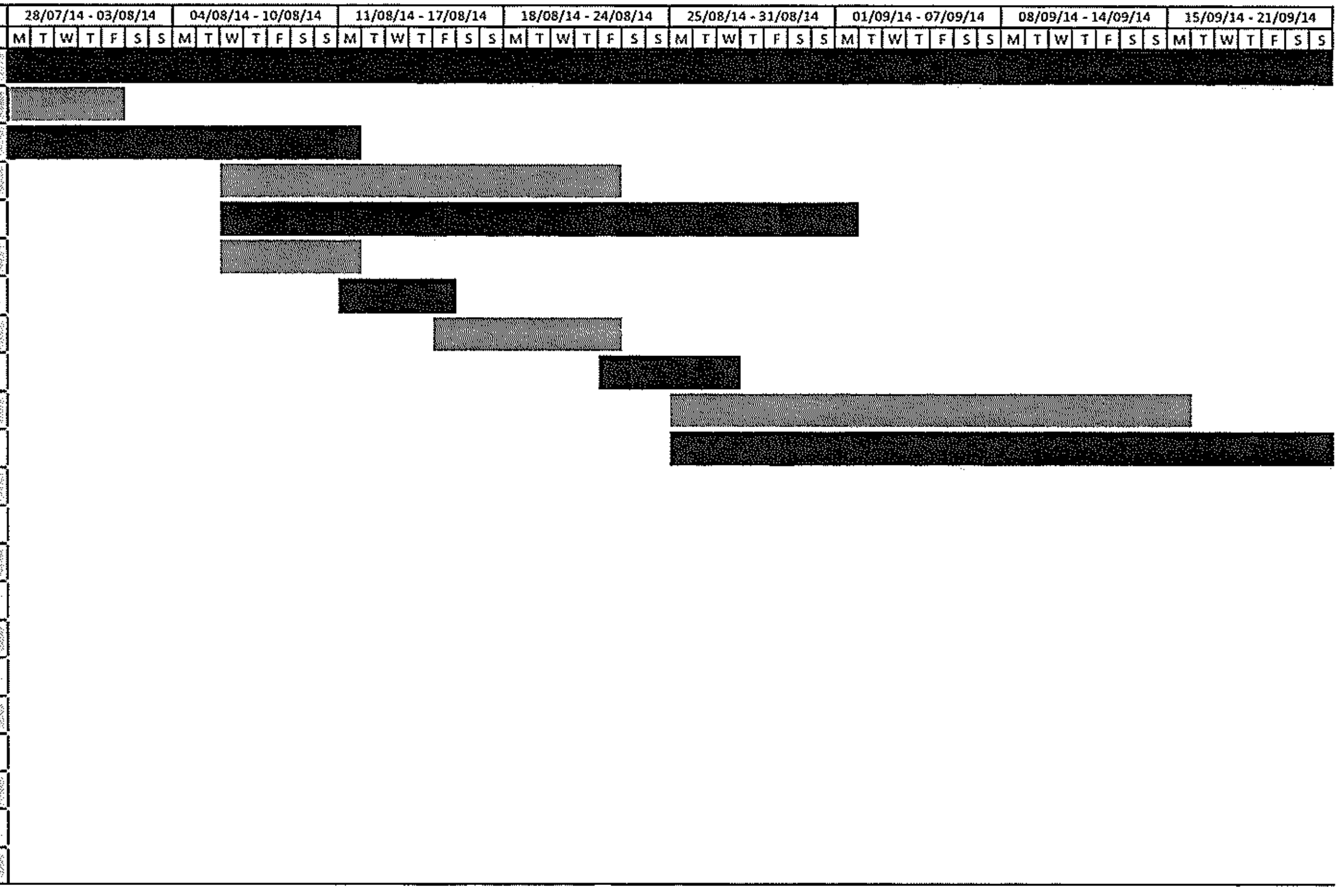
# Appendix

| Tasks | Start | End | Working Days |
|---|---|---|---|
| **Project Formulation** | 28-Jul-14 | 22-Sep-14 | 41 |
| Draft Preliminary Report | 28-Jul-14 | 01-Aug-14 | 5 |
| Final Preliminary Report | 28-Jul-14 | 11-Aug-14 | 11 |
| Draft Literature Review | 06-Aug-14 | 22-Aug-14 | 13 |
| Final Literature Review | 06-Aug-14 | 01-Sep-14 | 19 |
| Review of diffusion theory | 06-Aug-14 | 11-Aug-14 | 4 |
| Review of impact of concrete minerals and properties on chloride ingress | 11-Aug-14 | 15-Aug-14 | 5 |
| Review of existing models | 15-Aug-14 | 22-Aug-14 | 6 |
| Review of model validation method | 22-Aug-14 | 27-Aug-14 | 4 |
| Draft Project Proposal | 25-Aug-14 | 15-Sep-14 | 16 |
| Research Proposal | 25-Aug-14 | 22-Sep-14 | 21 |
| **Honours Project** | 23-Sep-14 | 24-Nov-14 | 45 |
| Analysis of 2013 results | 23-Sep-14 | 29-Sep-14 | 5 |
| Prediction for 3 months to 50 years | 29-Sep-14 | 06-Oct-14 | 6 |
| Analysis of 2014 results | 06-Oct-14 | 13-Oct-14 | 6 |
| Statistical Model Validation | 13-Oct-14 | 17-Oct-14 | 5 |
| Create user-friendly workbook (VBA code) | 17-Oct-14 | 24-Oct-14 | 6 |
| Draft honours project report | 13-Oct-14 | 10-Nov-14 | 21 |
| Final honours project report | 13-Oct-14 | 17-Nov-14 | 26 |
| Poster Presentation | 24-Oct-14 | 02-Nov-14 | 6 |
| Draft Seminar Presentation | 17-Nov-14 | 19-Nov-14 | 3 |
| Seminar Presentation | 17-Nov-14 | 24-Nov-14 | 6 |



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