CHAPTER V

APPLICATIONS

In the current chapter, a procedure used for estimating the life time service of a certain concrete structure will be presented. As it is stated in the objectives, the deteriorate model will be included only two phases: the initiation and the propagation phase. The service life is the total of both these periods and is defined as the appearance of the first crack. Firstly, some decisive parameters in these two phases will be discussed, after that a case study will be investigated in order to make the application clearer.

5.1 The initiation phase:

The initiation period defines the time it takes for chlorides to penetrate from the external environment through the concrete cover and accumulate at the embedded steel in sufficient quantity to break down the protective passive layer on the steel and thereby initiate an active state of corrosion. The length of this period is a function of the concrete quality, depth of cover, the exposure conditions and the threshold chloride concentration required to initiate corrosion. No damage (due to chlorides or corrosion) is assumed to occur during this period.

A simple approach to predicting the initiation period is to assume that ionic diffusion is the sole mechanism of chloride transport and to solve Fick's second law of diffusion using chloride diffusion coefficient to characterize the concrete under consideration. A further assumption made is that the concrete that is completely saturated. The decisive parameters are discussed as follows:

5.1.1 Initial chloride concentration:

Chloride concentration of surface C_0 is measured as the concentration at the surface of concrete within thickness of 0.5 in = 1.3 cm. Uji el al. 1990 observed that the chloride concentration of the exposed concrete surface of a marine structure was time dependent. On the basic of the observations, Uji el al 1990 proposed to assume that C_0 increases with the square root of time. That was the most convenient choice since Crank 1986 has published a solution of Fick's second law of diffusion under that condition. Besides Uji el al. 1990 this solution has been applied by Purvis 1994, Gautefall 1993 and Amey el al. 1996. However, in 1995 Swamy el al. has published a comprehensive amount of observations showing that C_0 not always increases with the square root of time. From the observations made by Swamy el al. 1995 it is concluded, that a better model of the increase of C_0 with time is a power function.

However, by observing the experimental data from Ema Kato el al. 2004, the chloride concentration of surface seems to be unchanged significantly after 100 days.

With assumption that initial chloride concentration is constant and capillary pores in concrete are filled with sea salt completely, the percentage of initial chloride concentration on cement weight can be computed as follows (Dubravka el al. 1995):

$$C_0 = \frac{V_C}{C} \times Q_{Cl^-} \tag{5.1}$$

Where:

C_0 = initial chloride concentration (% on cement weight)
Q_{Cl^-} = quantity of chloride in sea water
C = quantity of cement per 1 m^3 of concrete
V_c = volume of capillary pores which can be computed as follows (Powers 1958):

$$V_C = (w/b - 0.382 \times h) \times C \tag{5.2}$$

Where:

w/b = water binder ratio
h = degree of hydration

5.1.2 Threshold chloride concentrations:

Threshold chloride concentration is taken as the point at which the chloride content at the depth of reinforcement is high enough to start the propagation phase. The chloride threshold level is commonly presented as total chloride content expressed relative to the weight of cement. This is favored by the availability of relatively simple means to derive data, some of which are documented in standards (ASTM C114-83a 1983 and British Standard 1881, 1988). There is no fix value for the threshold chloride concentration because a certain concentration should be associated with a particular risk of corrosion (Glass GK and Buenfeld NR 1997). Some values from standards can be seen from table 5.1:

Table 5.1 Threshold chloride from standards

Source	Threshold chloride
ACI 222	0.20
ACI 318	0.20
BS 8110	0.4
Australian codes	0.60
Norwegian codes NS 3420	0.4
RILEM	0.4

Note: Values specified by ACI 222 and BS 8110 are codal limits and not true threshold values for onset of corrosion.

Furthermore, chloride levels required initiating the corrosion of steel determined in the field on reinforced concrete structures, on concrete and mortar specimens exposed laboratory and outdoor environments are also illustrated in table 5.2

Table 5.2 Threshold chloride from literature

Source	Exposure	Sample	Threshold chloride
Stratful el al. 1975	Outdoors	Structure	0.17 -1.4
Vassie 1984	Outdoors	Structure	0.2 -1.5
M. Thomas 1996	Outdoors	Concrete	0.5 -0.7
Hener and Bohni 1986	Laboratory	Mortar	0.25 -0.5
Henriksen 1993	Outdoors	Structure	0.3 -0.7
Treadaway el al. 1989	Outdoors	Concrete	0.32 -1.9
Bamforth and Chapman -Andrews 1994	Outdoors	Concrete	0.4
Page el al. 1986	Laboratory	Paste	0.4
Hansson and Sorensen 1990	Laboratory	Mortar	0.4 -1.6
Schiessl and Raupach 1990	Laboratory	Concrete	0.5 -2
Thomas el al 1990	Outdoors	Concrete	0.5
Tuutti 1993	Laboratory	Concrete	0.5 -1.4
Locke and Siman 1980	Laboratory	Concrete	0.6
Lambert el al 1991	Laboratory	Concrete	1.6 -2.5
Lukas 1985	Laboratory	Structure	1.8 -2.2

5.2 The propagation phase:

Propagation phase is defined as a phase of corrosion of embedded steel. During the propagation phase, the reinforcement actively corrodes. The propagation phase begins once the depassivation of the reinforcing steel has occurred and ends when a specified amount of section loss has occurred. The duration of the propagation phase is the total time until concrete first cracking, caused by formation of corrosion products from the steel reinforcement, which occupy a larger volume than the parent steel. Once the corrosion of the reinforcement is initiated, the area of the reinforcement is reduced by a corrosion speed q (mm of material loss from reinforcement diameter per year). Many parameters influence q, namely the chloride content, the presence of oxygen, the diffusion coefficients, the electrical resistivity of the concrete, the presence of cracks and the formation of macro-cells. The range of observed corrosion speeds varies from 0.1 mm/year to a few mm/year including pitting corrosion (Gonzalez et al.).

On the other hand, the rate corrosion can be investigated clearly by applying the empirical equation of Morinaga:

$$q = [0.51-7.60xN+44.97x(w/b)^{2}+67.95xNx(w/b)^{2}]x\ d / c^{2} \quad (5.3)$$

Where:

q = the rate of corrosion in units of 10^{-4} g/cm^2.year

N = the chloride concentration (%),

w/b = the water binder ratio
d = the diameter of the reinforcement (mm)
c = the concrete cover (mm).

As it is stated in the theorical background earlier, there are three different approaches for estimating the time of propagation period. They consist of Bazantš mathematical model, Morinagaš empirical equation and ४uping Liuš model. Bazantš mathematical model has not verified by the experimental data yet and ४uping Liuš model is quite complicated since they take in account the many different kinds of formation of rust products. Furthermore, the length of the propagation phase is usually very short, in compared with the initial phase. Therefore, in the current application, Morinaga is applied since this approach is simpler and easier for practical application compared with two other models. In addition, previous researches suggest that the time for this stage may be approximately 5 years for bare bar reinforcement, and may be an additional 1 to 7 years for epoxy cover bar (Covino J. BS et al. 2000;Clear K 1998; Weyers RE et al. 1997).

5.3 Procedure of application:

The service life of certain reinforced concrete structure can be estimated step by step by the following suggested procedure of the current study:

1) Compute initial chloride concentration (equation 5.1) based on quantity of chloride in sea water, quantity of cement per 1 m^3 of concrete and water binder ratio.

2) Compute chloride diffusion coefficient (equations 4.9, 4.10, 4.11 or 4.12) based on water binder ratio, the percent of fly ash, rice husk ash or both.

3) Choose the desire chloride threshold concentration from 0.2 to 0.6 (table 5.1 and 5.2).

4) Compute the initial time t_1.

5) Compute the time t_2 for propagation phase (equation 5.3 and 2.23).

6) Compute the service life = $t_1 + t_2$

Based on above computing procedure, there are two approaches by that way the resistance to chloride ingress of concrete can be improved or computed in order to obtaining the desire service life time. The first one is a basic way (see Figure 5.1). By that diagram, a service life time of concrete in a certain environment such as Thailand or Vietnamese marine environment can be predicted or estimated. After that, a large maintains or repairment will be applied in order to lengthen the service period of concrete structure. It means that the output value for this diagram is the estimative service life time. And the input data include the information about the environment (chloride condition for the current case) as the boundary conditions and the mix proportion of concrete structures as well as the cover thickness and rebar dimension. The mix proportion consists of water binder ratio, the percent replacement of rice husk ash or fly ash or both. These input data will be applied into Ficks second law. The result will show the estimative time for maintaining or repairing the concrete structure.

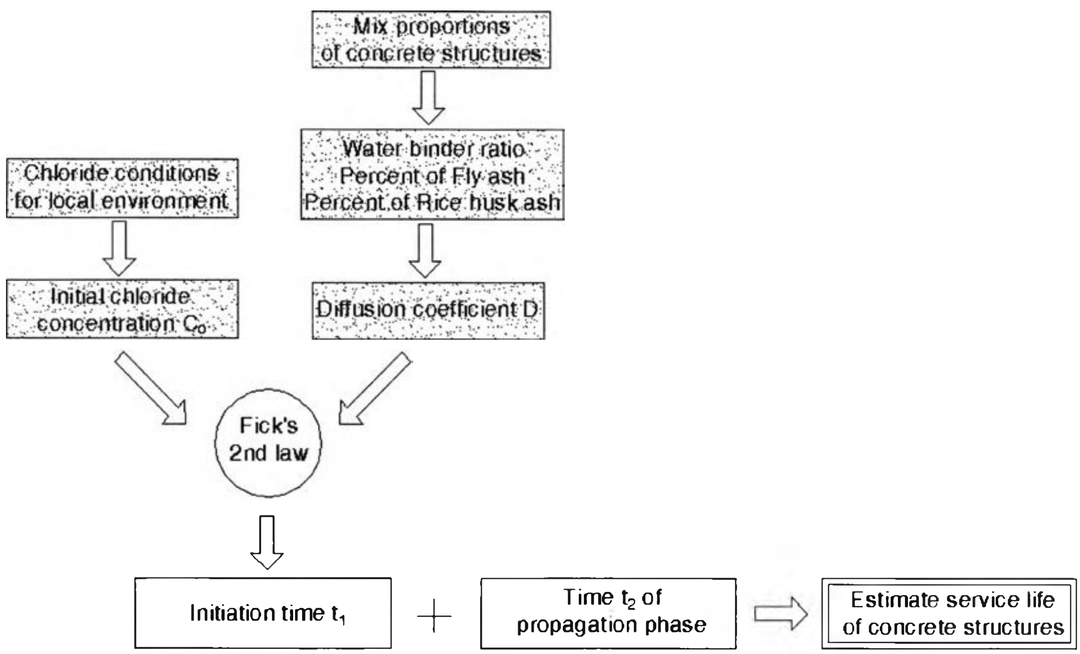

Figure 5.1 Diagram for estimate service life of concrete structures in marine environment

The second diagram is another approach which contraries to the first one (see Figure 5.2). Follow this way, besides the necessary boundary conditions, the service life time is now treated as input data. The current service life is known in advance. It means that the life time is now determined by designers beforehand for a certain concrete structure in order to achieve some specific aims. Both these input data will flowed through Ficks second law and the result is the value of diffusion coefficient. Based on this value and the above expression (4.9), (4.10), (4.11) and (4.12), a suitable mix proportion for current concrete structure is obtained. On the other hand, with known chloride diffusion coefficient, the cover thickness or dimension of rebar can be designed.

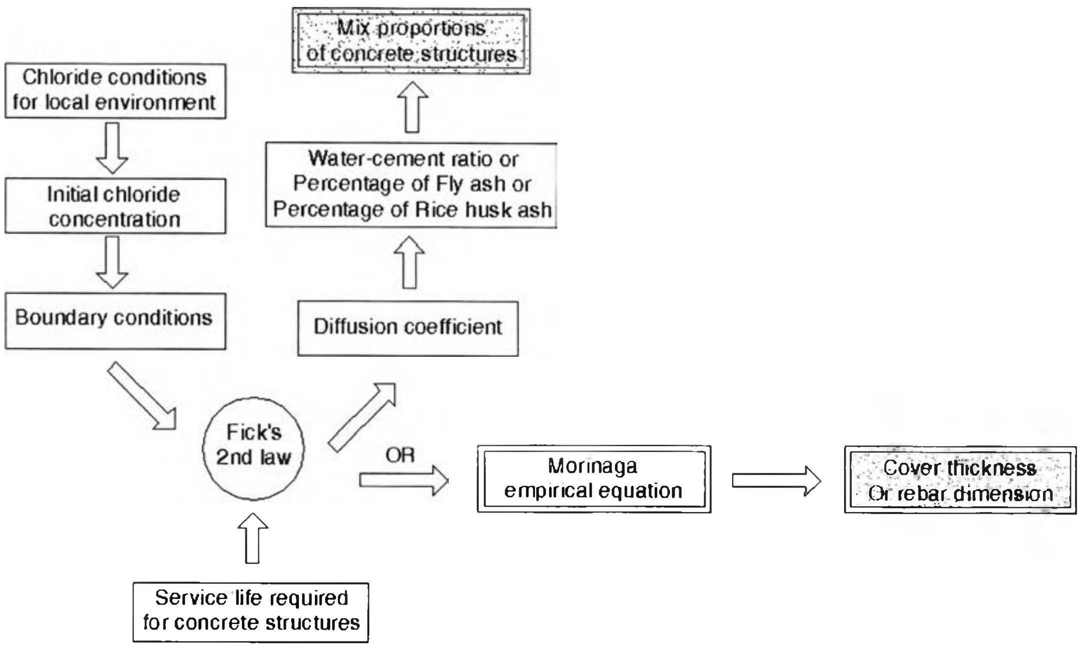

Figure 5.2 Diagram for estimate mix proportion or cover thickness or dimension of rebar based on desirable service life

5.4 Examples of application:

In order to make the application more clearly, a case study of the Laem Pak Bia project in Thailand and the Can Tho Bridge in Vietnam are investigated.

5.4.1 Laem Pak Bia project:

Laem Pak Bia project is also known as a new shortcut to the South - Samut Sakhon - Laem Phak Bia - Cha Am which contains many subprojects. In this case study, only the sea bridge across the Gulf of Thailand is investigated because it is the most interesting part of overall the Laem Pak Bia project.

5.4.1.1 Predict service life procedure:

5.4.1.1.1 Input values for the application:

The input values for the case study sea bridge across the Gulf of Thailand - Laem Pak Bia project are as follows:

Table 5.3 Properties of concrete for pier (submerged zone)

Maximum water binder ratio	0.42
Maximum cover thickness (mm)	50
Rebar dimension (mm)	32

5.4.1.1.2 Computing procedure:

1. Table 5.4 presents the initial chloride concentration based on chloride concentration in sea water in Gulf of Thailand and water binder ratio (for more details see appendix E The long term degree of hydration is estimated as 100% of the theoretical maximum achievable hydration, based on the water binder ratio. For water binder ratios greater than or equal to 0.42, there is sufficient capillary porosity for all of the cement to react so that this theoretical maximum is 1, while for lower water binder ratios, this theoretical maximum degree of hydration is given by [w/b)/0.42](Mindess S. and Young JF, 1981). Therefore, in the current case study, the maximum degree of hydration is assumed as 1.0

Table 5.4 Initial chloride concentration

Maximum water binder ratio w/b	0.42
Maximum degree of hydration (assumed)	1.0
Chloride concentration in sea salt (kg/m^3)	1.204
Initial chloride concentration (%)	4.5752

2. Table 5.5 illustrates the chloride diffusion coefficient based on water binder ratio because the current case is ordinary Portland cement.

Table 5.5 Chloride diffusion coefficient

Water binder ratio w/b	0.42
Chloride diffusion coefficient (m^2/s)	25.48 x10^{-12}

3. The threshold chloride concentration is chosen as 0.2 because of the safe side. The smaller threshold chloride concentration is, the lower service life is. Therefore, $C_r = 0.2$ %

4. The initial time is computed about 43.6 years for cover thickness of 50 mm. In addition, the following figures present some values of initial time t_I versus cover thickness of concrete structure.

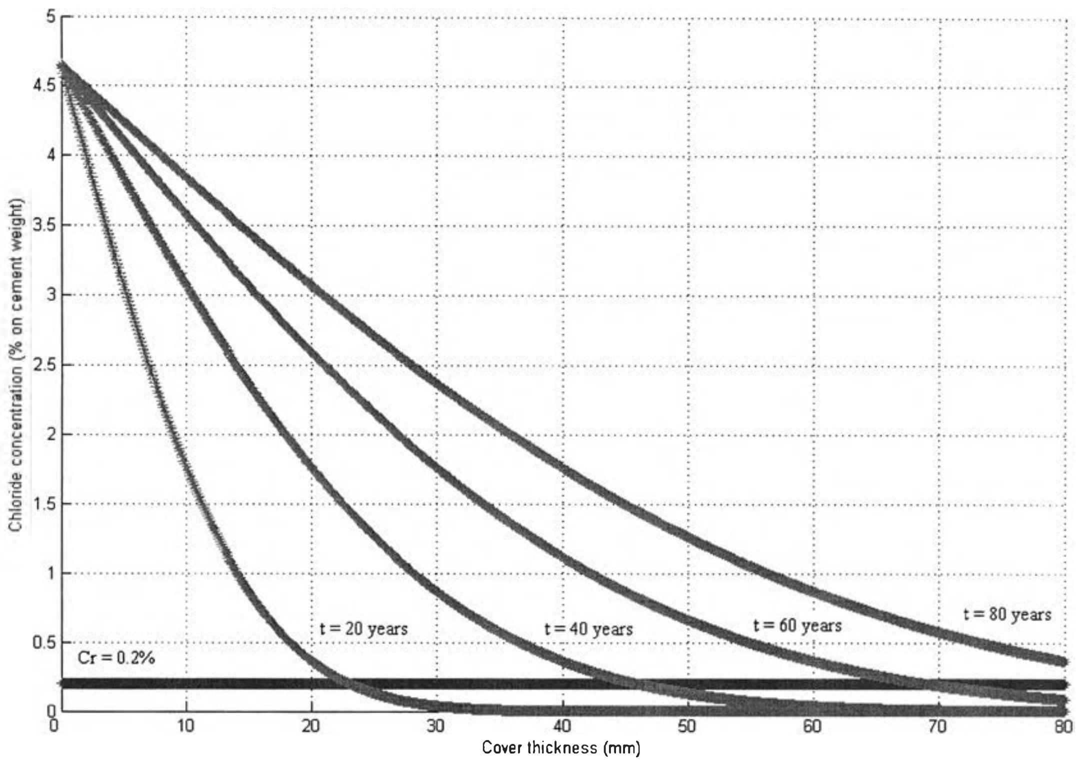

Figure 5.3 Initial time versus cover thickness

From the above figure, the concrete structure may have the initial time about 43.6 years according to the cover thickness is 50 mm. This length of initial period is quite in accordance to the report of ACI committee 29 "Guide to durable concrete." In ACI committee 29 report, the initial time is 50 years when the surface chloride concentration is 5 percent on cement weight, water binder ratio is 0.4 and cover thickness is 50 mm. Figure 5.4 presents the comparison between the current case study and ACI committee 29 report:

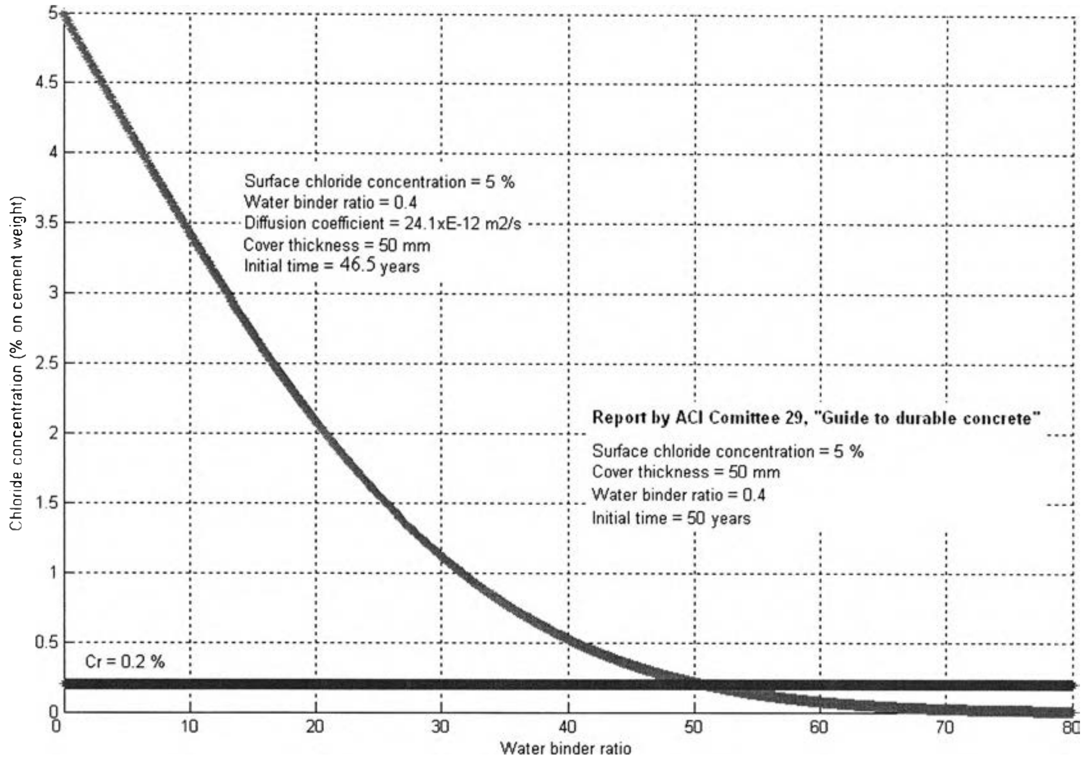

Figure 5.4 ACI committee 29 report and current case study

In addition, regarding technical specifications of the coast to coast bridge, fly ash can be added to the mix proportion from 10% to 40%. The influences of fly ash can be investigated by the Figure 5.5 as follows:

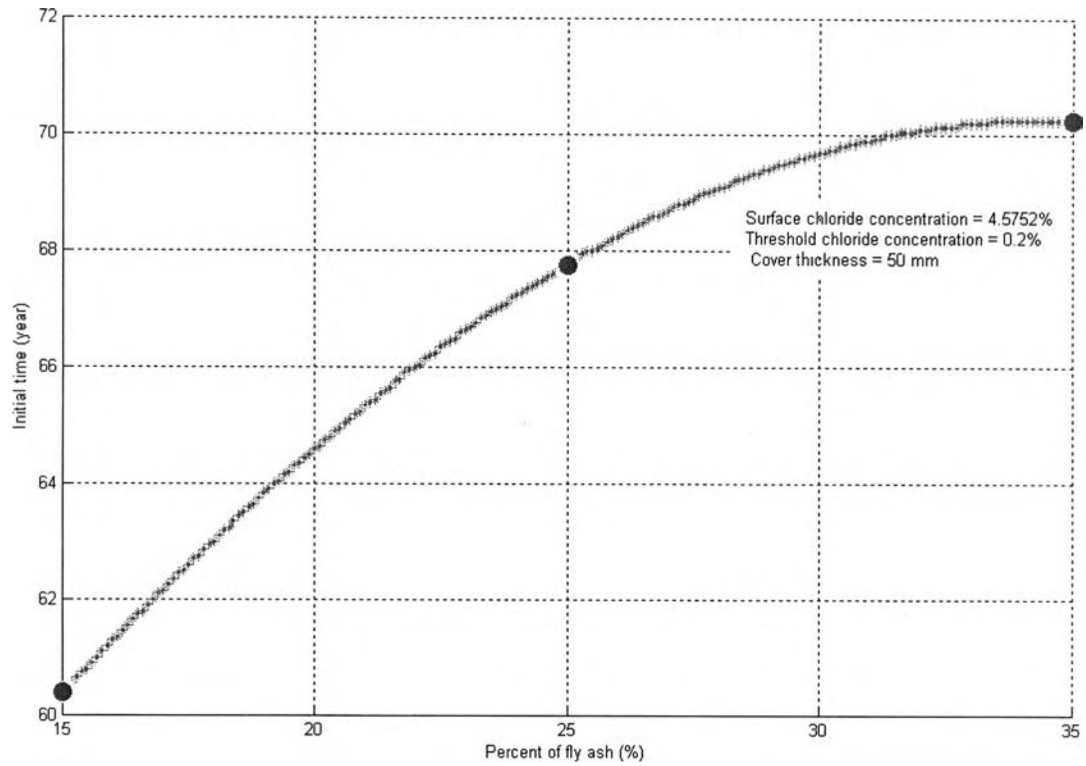

Figure 5.5 The impact of fly ash on initial time

From these above figures, the influence of fly ash on the initial time is remarkable. For example, with addition of 35% fly ash, the time for the initiation phase is nearly two folds, in compared with the plain cement case.

5. Figure 5.6 presents the section of concrete structure used to compute the time for the propagation phase.

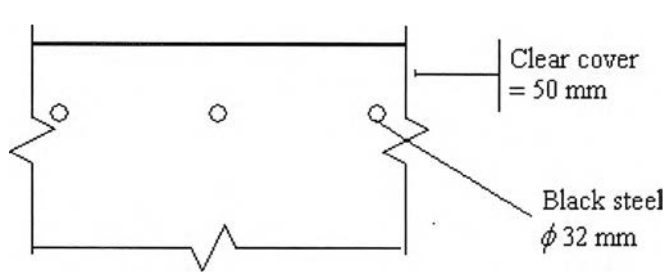

Figure 5.6 The section of concrete structure

Substitute the values of cover thickness and the dimension of black steel into equation (5.3), the corrosion rate 37.78 g/m^{2}year is obtained. After that, the time of propagation phase is estimated about 1.66 years based on the equation (2.23). The time of the second stage is very small, compared with the first period. It is completely compatible with other conclusion from literature.

Finally, the total time or the service life is 45.3 years. After this life time, the bridge needs to be inspected as well as maintained. In order to perform this procedure easier in the future, a small Matlab code is built (see. Appendix)

The above procedure can be summarized by the follow work sheet in order to get the overview of the computing approach.

Water binder ratio*	Degree of hydration*	Chloride concentration*	Equation	Initial chloride concentration (%)
0.42	1.0	1.204	(5.1) and (5.2)	4.5752

Water binder ratio*	Case*	Equation	Chloride diffusion coefficient (m/s²)
0.42	Ordinary Portland cement	(4.9)	25.48 x10^{-12}

Initial chloride concentration (%)	Chloride diffusion coefficient (m/s²)	Chloride threshold* (%)	Cover thickness* (mm)	Equation	Initial time t_1 (year)
4.5752	25.48 x10^{-12}	0.2	50	Fick's 2nd law	43.6

Water binder ratio*	Rebar dimension* (mm)	Cover thickness* (mm)	Equation	Propagation time t_2 (year)
0.42	32	50	(5.3) and (2.23)	1.66

Initial time t_1 (year)	Propagation time t_2 (year)	Equation	Service life (year)
43.6	1.66	$t_1 + t_2$	45.3

Note: *Available values from current concrete structure

Figure 5.7 Work sheet for computing approach to estimate service life of the sea bridge in Laem Phak Bia project

5.4.1.2 Design mix proportions procedure:

5.4.1.2.1 Input values for the application:

The input values for this approach with the same project are as follows:

Table 5.6 Input values of design water binder ratio

Design service life (year)	60
Maximum cover thickness (mm)	50
Rebar dimension (mm)	32

The expected outcome for the current case is the water binder ratio.

5.4.1.2.2 Computing procedure:

Because the water binder ratio is one the main parameters for overall procedure, there is only one way to perform this task. Water binder ratio will be assumed a trial value in advance. After that, it can be easy to follow the same approach as the procedure of predicting service life mentioned earlier. The service life collected from the calculation will be then compared with the desire value .If not equal, a new trial value of water binder ratio is chosen based on the previous value and a same procedure will be performed until obtaining the service life as expected. Since this task is time-consuming, a small Matlab source code is developed for easier and faster computing (see Appendix G). By applying this approach, the water binder ratio is computed as 0.33 for 60 year service life with the case of plain concrete.

5.4.1.3 Design cover thickness procedure:

5.4.1.3.1 Input values for the application:

The input values for this approach with the same project are as follows:

Table 5.7 Input values of design cover thickness

Design service life (year)	60
Maximum water binder ratio	0.42
Rebar dimension (mm)	32

The outcome for the current case is the cover thickness.

5.4.1.3.2 Computing procedure:

Because the cover thickness is one of the main parameters for overall procedure, there is only one way to perform this task. Cover thickness will be assumed a trial value in advance. After that, it can be easy to follow the same approach as the procedure of predicting service life mentioned earlier. The service life collected from the calculation will be then compared with the desire value .If not equal, a new trial value of cover thickness is chosen based on the previous value and a same procedure will be performed until obtaining the service life as expected. Since this task is time-consuming, a small Matlab source code is built for easier and faster computing (see Appendix I). By applying this approach, the cover thickness is computed as 67 mm for 60 year service life with the case of plain concrete.

5.4.1.4 Design rebar dimension procedure:

5.4.1.4.1Input values for the application:

Because the rebar used in the current case is bare bar therefore its lifetime can not be more than 5 years. So service life is designed as 89 years and the input values for this approach with the same project are as follows:

Table 5.8 Input values of design rebar dimension

Design service life (year)	45.2
Maximum water binder ratio	0.42
Maximum cover thickness (mm)	50

The outcome for the current case is the rebar dimension.

5.4.1.4.2 Computing procedure:

Because the rebar dimension is one of the main parameters for propagation phase, there is easier to compute the rebar dimension. First, with the initial time and the total service life the time of propagation phase obviously obtained. After that, by applying the Morinaga's equations, rebar dimension can be obtained. In order to perform the procedure easier, a small Matlab source code is also developed (see Appendix G). By applying this approach, the rebar dimension is computed as 34 mm for 43.2 year service life with the case of plain concrete.

5.4.2 Can Tho bridge:

The Can Tho Bridge is a cable-stayed bridge of 500m main span with steel box girder in the central part of main span and prestressed concrete box girder in the remaining part of the structure. The 2.75km-long bridge spanning the Mekong River tributary links Vinh Long Province with Hau Giang Province. When completed, expected in 2008, Can Tho Bridge will be the longest cable-stayed bridge in Southeast Asia.

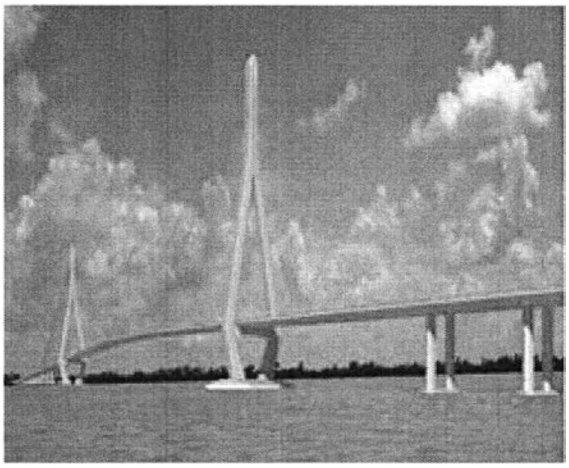

Figure 5.8 The design of Can Tho Bridge

5.4.2.1 Predict service life procedure:

5.4.2.1.1 Input values for the application:

The input values for the case study Can Tho Bridge are as follows:

Table 5.9 Properties of concrete for abutment wall (submerged zone)

Maximum water binder ratio	0.55
Maximum cover thickness (mm)	70
Rebar dimension (mm)	20

5.4.2.1.2 Computing procedure:

1. Table 5.10 presents the initial chloride concentration based on chloride concentration in sea water in Vietnam (for more details see Appendix E and water binder ratio.

Table 5.10 Initial chloride concentration

Maximum water binder ratio w/b	0.55
Degree of hydration (assumed)	1
Chloride concentration (kg/m^3)	1.225
Initial chloride concentration (%)	20.58

2. Table 5.11 illustrates the chloride diffusion coefficient based on water binder ratio because the current case is ordinary Portland cement, no partially replacement of Portland cement by fly ash as well as rice husk ash.

Table 5.11 Chloride diffusion coefficient

Water binder ratio w/b	0.55
Chloride diffusion coefficient (m^2/s)	37.86x10^{-12}

3. The threshold chloride concentration is chosen as 0.2 because of the safe side. The smaller threshold chloride concentration is, the lower service life is. Therefore, C_r = 0.2 %

4. The following figures will present some value of initial time t_I versus cover thickness of concrete structure.

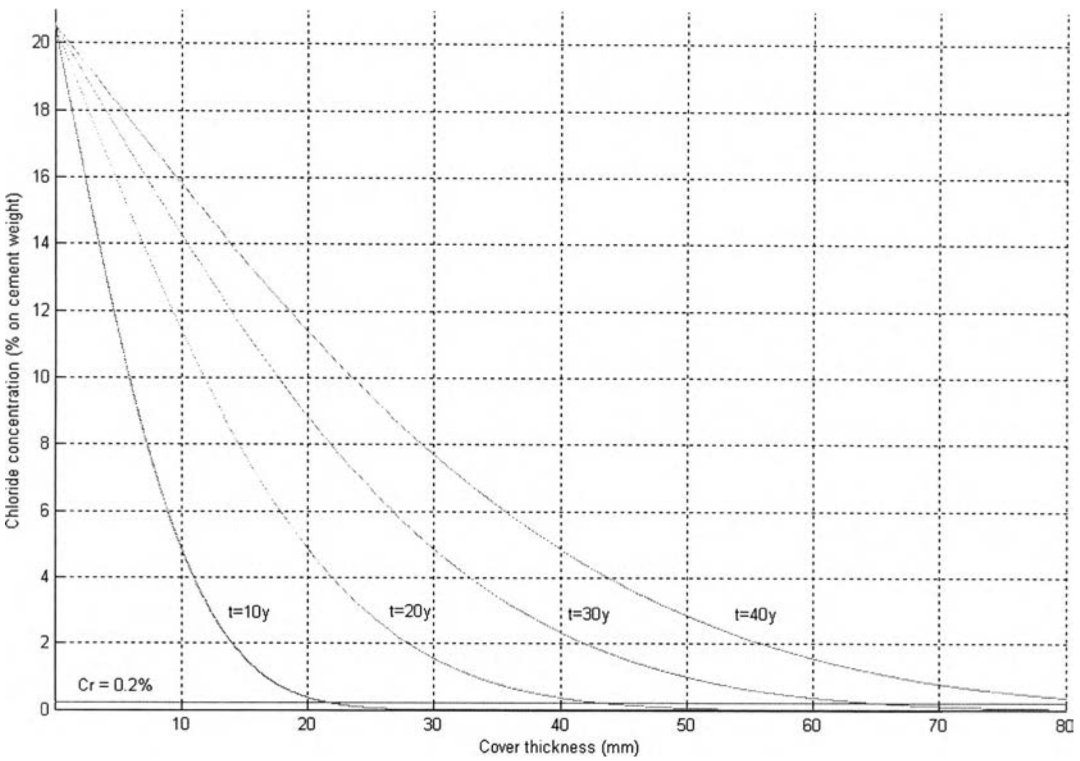

Figure 5.9 Initial time versus cover thickness

From the above figure, the concrete structure has the initial time about 32.1 years if the cover thickness is at least 70 mm.

5. Figure 5.10 presents the section of concrete structure used to compute the time for the propagation phase.

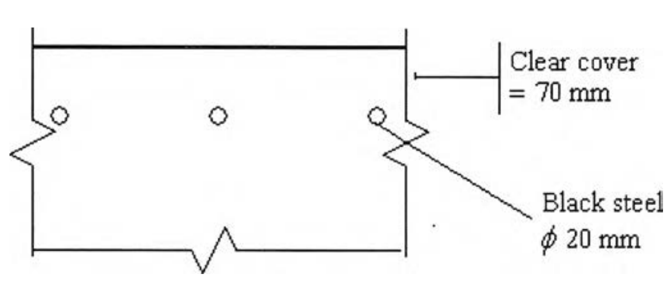

Figure 5.10 The section of concrete structure

Substitute the values of cover thickness and the dimension of black steel into equation (5.3), the corrosion rate 23.37 g/m^{2}year is obtained. After that, the time of propagation phase is estimated about 3.02 years based on the equation (2.23). Therefore, the total service life is 35.12 years.

The above procedure can be summarized by the follow work sheet in order to get the overview of the computing approach.

Water binder ratio*	Degree of hydration*	Chloride concentration*	Equation	Initial chloride concentration (%)
0.55	1.0	1.225	(5.1) and (5.2)	20.58

Water binder ratio*	Case*	Equation	Chloride diffusion coefficient (m/s^2)
0.55	Ordinary Portland cement	(4.9)	37.86 $\times 10^{-12}$

Initial chloride concentration (%)	Chloride diffusion coefficient (m/s^2)	Chloride threshold* (%)	Cover thickness* (mm)	Equation	Initial time t_1 (year)
20.58	37.86 $\times 10^{-12}$	0.2	70	Fick's 2nd law	32.1

Water binder ratio*	Rebar dimension* (mm)	Cover thickness* (mm)	Equation	Propagation time t_2 (year)
0.55	20	70	(5.3) and (2.23)	3.02

Initial time t_1 (year)	Propagation time t_2 (year)	Equation	Service life (year)
32.1	3.02	$t_1 + t_2$	35.12

Note: *Available values from current concrete structure

Figure 5.11 Work sheet for computing approach to estimate service life of the Can Tho bridge

5.4.2.2 Design mix proportions procedure:

The input values for this approach with the same project are as follows:

Table 5.12 Input values of design water binder ratio

Design service life (year)	50
Maximum cover thickness (mm)	70
Rebar dimension (mm)	20

The outcome for the current case is the water binder ratio. And for the case of service life 50 years, the water binder ratio should not be more than 0.46.

5.4.2.3 Design cover thickness procedure:

The input values for this approach with the same project are as follows:

Table 5.13 Input values of design cover thickness

Design service life (year)	50
Maximum water binder ratio	0.55
Rebar dimension (mm)	20

The outcome for the current case is the cover thickness and the covet thickness should not be less than 99 mm

5.4.2.4 Design rebar dimension procedure:

Because the rebar used in the current case is bare bar therefore its lifetime can not be more than 5 years. So service life is designed as 89 years and the input values for this approach with the same project are as follows:

Table 5.14 Input values of design rebar dimension

Design service life (year)	35
Maximum water binder ratio	0.55
Maximum cover thickness (mm)	70

The time of propagation phase is 2.9 years. Therefore, the rebar dimension is designed as maximum 22 mm.

In order to give the recommendation for concrete structure in Thailand and Vietnam marine environment as ACI committee 29 report, the same above procedure with desire service life 50 years and cover thickness 50 mm are performed. Finally, the water binder ratio should be not more than 0.41 and 0.38, for Thailand and Vietnam marine environment, respectively. In addition, from these recommendations, it can be obviously seen that the remarkable influence of local environment on the service life of concrete structures. .