Durability of Reinforced Concrete Structures in Corrosive Environments in Conditions of Climate Change

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Abstract
Reinforcing steel corrosion is the primary cause of concrete deterioration of reinforced concrete (RC) structures when they are placed in maritime environments. The study dwell on the mechanism of chloride ingress, corrosion initiation and problems associated with durability of reinforced concrete infrastructures in corrosive environments in conditions of climate change. Chloride-induced corrosion presented in Fib Model Code Service Life Design (fib MC- SLD) and Life-365 Model software was carried out using various supplementary cementitious materials (SCMs) and concrete strength classes to predict the initiation time and propagation. Durability recommendations were made based on the results obtained which could help practicing engineers to make selection for reinforced concrete structures (RC) made of various concrete types in order to reduce chloride-induced corrosion initiation within the service life of a structure in severe marine environments in conditions of climate change. The study found that the SCMs, concrete strength classes and concrete cover depths are good approaches that can be employed to improve the durability of reinforced concrete infrastructures in aggressive environments. The study also found that changing climate can affect the environmental conditions in a way that can accelerate corrosion initiation thus affecting the structural capacity and safety.

Keywords: *Climate change, corrosion, design life, durability, marine environments, reinforced concrete.*

1.0 Introduction

Concrete is the most widely known construction material in the world owing to its readily availability and material properties. It is a composite material composed of coarse aggregates bonded together with fluid cement which harden with time. Limestone is the predominant raw material for the cement in concrete. Concrete can equally be made with silica fume, slag cement and pulverized ash. In Portland cement concrete, when the aggregates are mixed together with the dry cement and water, they form a fluid mass that is easily molded into shape. The cement reacts chemically with the water and other ingredients to form a harder matrix which binds together into a durable stone-like material that has many applications. At times, additives such as super-plasticizers or pozzoloans are added in the mixture to improve the physical characteristics of the finished product. Concrete is generally good in compression but poor in tension and as such, most concrete is poured with reinforcing materials (steel bar) embedded to provide tensile strength, yielding reinforced concrete.

The corrosion of reinforced steel is the most critical problem that affects the durability of reinforced concrete (RC) in marine environments or those in contact with deicing salts are in particular threat of being subject to corrosion. Reinforced concrete deterioration in maritime environments can be caused by chemical, physical and mechanical factors and can be influenced by external and internal to the concrete infrastructure. The climate influenced the physical and chemical deterioration, hence, affecting the performance, serviceability and safety of the concrete at long-term (Wang et al., 2010).

Figure 1.1: Corrosion of reinforcement by chloride attack in a marine environment (Walraven, 2008)

Corrosion induced by chloride ingress has been known as an essential factor decreasing the service life of RC structures (Bastidas-Arteaga, 2013). Deterioration caused by chloride-induced corrosion is the main risk to the durability of marine and coastline concrete structure. A thin passive layer of oxide covered the steel reinforcement that protects it from oxygen and water which may cause corrosion and induce rust can be destroyed by a process known as "depassivation" when chloride ions penetrates the concrete and accumulate to a critical level on the surface of steel reinforcement. Corrosion on the steel surface follows and the corrosion results cause significant expansion. This creates internal stress and causes cracking (Wang et al., 2010).

Atmospheric penetration of carbon dioxide is the primary cause of carbonation. It considerably decreases alkalinity which invariably, increases the susceptibility of reinforcing steel to corrosion as a result of passivation. The direct consequence of carbonation is reduction at the same time decrease in PH, which if not checked, will ultimately leads to corrosion and cracking followed by spalling (Wang et al., 2010)

Concrete corrosion induced by chloride and carbonation is thoroughly influenced by surrounding factors such as humidity and temperature. All these factors – humidity, temperature and carbon dioxide concentrations will differ due to increasing green-house effects and climate change (Bastidas-Arteaga & Stewart, 2015; Bastidas-Arteaga et al., 2013). It has become an integral study issue in the field of civil engineering globally the impact of climate change on the performance of concrete infrastructures (Bastidas-Arteaga & Stewart, 2015), as it is capable of reducing the time to collapse by up to 31 percent for reinforced concrete expose to ingress of chloride (Larrard et al., 2014). In view of the possibility that CO_2 concentration in atmosphere may increase up to three times of the present level and an average global temperature may rise up to 43 degree Fahrenheit by 2100 in a high emission setting, the threat of damage of concrete structures may be significantly affected (Wang et al., 2010).

Other sources of deterioration are the attack by sulphate which is also a concern for concrete elements in low-lying coastal regions. Reaction between aggregate and alkali which is a main constituent of concrete can result in expansion and cracking. Freeze thaw cycles which cause expansion of concrete, and also absorbed by capillary action, thermal cycles will be experienced with changes in the ambient temperature.

1.1 Aim

The aim of this study is to estimate the design specifications which are needed to reduce the possibility of corrosion initiation within the design life of a structure to an acceptable level in conditions of climate change.

2.0 Methodology

The study is aimed to produce a set of design specifications based on provisions for concrete composition and cover for use expose to various severe environments. Series of simulations were carried out using the fib MC-SLD and Life-365 models. The design parameters tested by simulation are concrete strength class; cement composition and concrete cover depth.

2.1 Parameters for modeling

The following parameters below were used to allow exposure environment and a variety of concrete composition to be measured.

2.2 Critical chloride threshold

In this study, the threshold value of 0.05% weight of concrete was adopted as the critical chloride threshold. The author assumed the density of concrete as 2400kg/m^3 giving a chloride threshold of 1.2kg/m^2. It follows in accordance with various data in published literatures and is the value adopted by Japanese Standards of Civil Engineers (JSCE, 2010). The study also assumed that the cement content of all concrete models is 350kg/m^3. This is in compliance with the lowest cement content suggested by British standards 206-1.

2.3 Design service life

Design life is an important governing parameter as it makes a key difference in a performance based approach (Life-365, 2014). In this study a design life of 100 years period was considered which is in line with the British standards provision for monumental building structures, bridges and other related civil engineering infrastructures (Neville, 2008).

2.4 Concrete composition

Four various types of cement were chosen inclusive of PC, FA, SF and GGBFS to model the influence of supplementary cementitious materials (SCMs). Simulations adopting three various strength classes of each cement types to model the impact of changing the water-cement ratio on chloride ingress was carried out.

2.5 Cover to reinforcement depth

One of the important parameter to prevent corrosion occurrence of reinforcement in concrete durability is the concrete cover depth. The aggressive nature of marine environment requires higher concrete cover than the minimum structural requirements for durability to be attained.

2.6 Exposure conditions

In this study effort is made to focus on XS1 and XS3 zone classification stated in EN 206-1 simulated under the exposure of maritime chlorides. Data for marine environments surface chloride concentrations differ among published literatures considering various exposure zones. These data are based on published literatures (King, 2012; Bamforth, 2004)

3.0 Results

3.1 Concrete grade

Figure 3.1 illustrates the effect of concrete quality as stated by concrete strength class on the rate and chloride penetration depth. The comparison on the effect of concrete grade was made by considering only the ordinary PC as type of cement and the respective water-cement ratios.

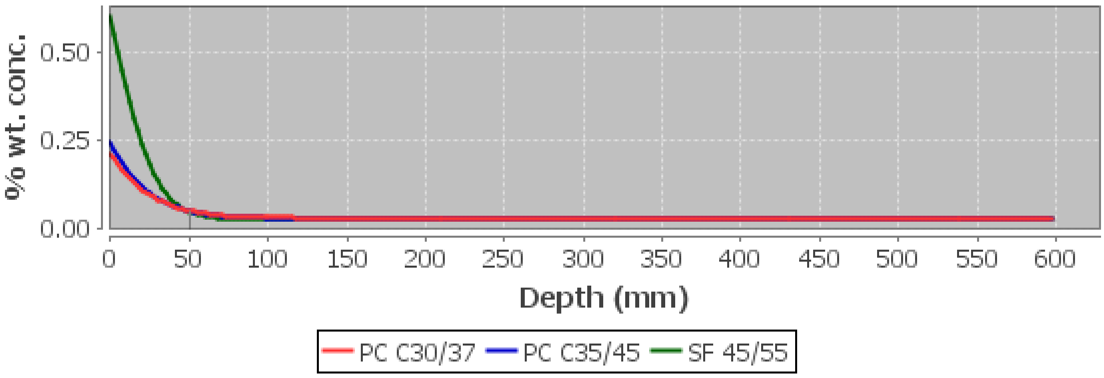

Figure 3.1: Chloride concentration versus depth

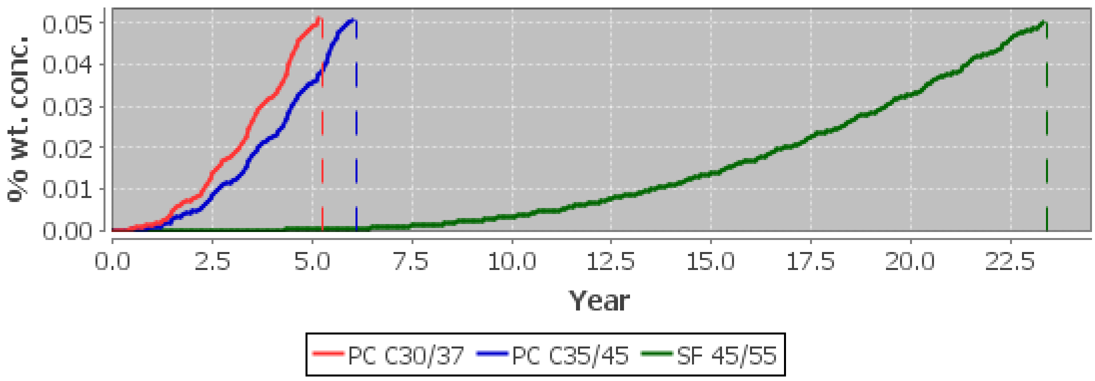

Figure 3.2: Chloride concentration versus time

3.2 Cement type

Figure 3.2 presents the effect of various supplementary cementitious materials (cement type) on the rate and depth of chloride penetration. For the purpose of comparison of the effect of SCMs, only concrete strength class C45/55 was considered.

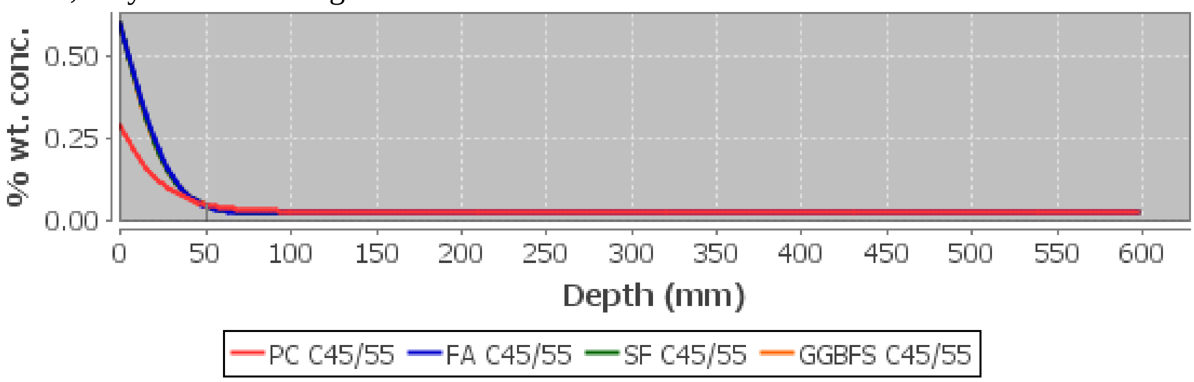

Figure 3.2: Chloride concentration versus depth

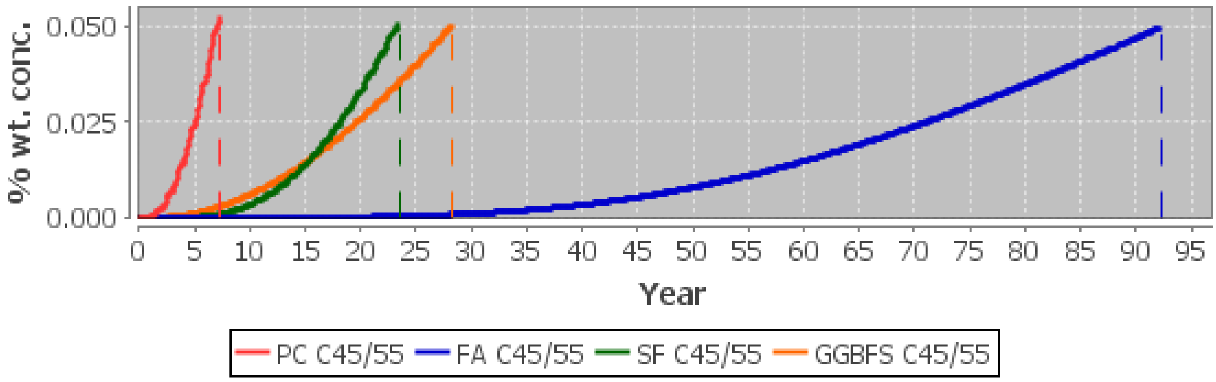

Figure 3.3: Chloride concentration versus time

Figure 3.3 shows the chloride concentration at a depth of 50mm from the surface. Chloride ingress increased resistance of FA is considerably visible. Its performance considerably outweighs other SCMs with about 12 times the initiation time than ordinary PC.

3.3 Diffusivity

This unit presents the result from Life-365 the apparent coefficient of diffusion considering different cement types but the same strength class (C45/55).

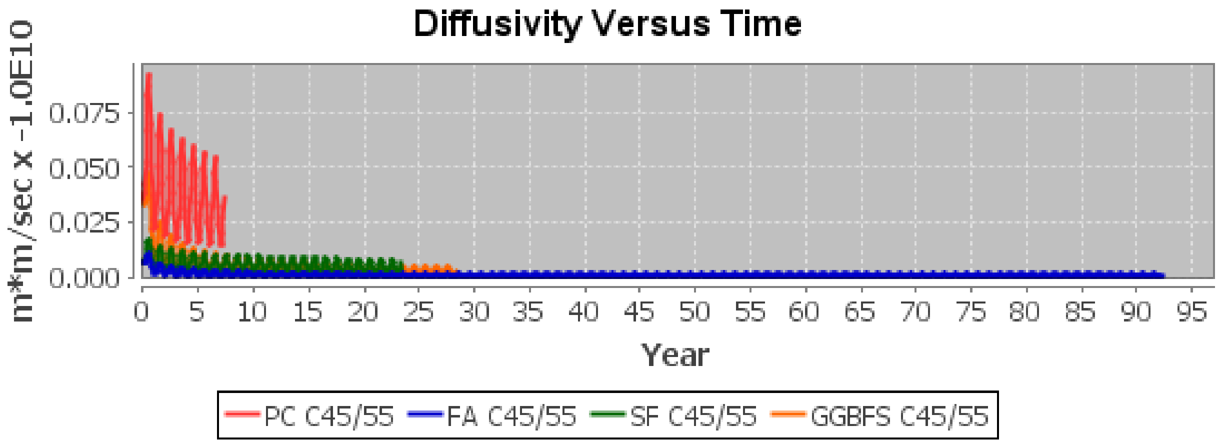

Figure 3.4: Diffusivity versus time

Figure 3.4 shows the apparent coefficient of diffusion of different SCMs. It revealed that diffusivity is time depended as aging factor decrease with time. FA and GGBFS shows very low diffusivity compared to other SCMs especially PC cement type.

Table 1: Results for prediction of initiation time from the models

Cement type	Model	Concrete strength class	Reinforcement concrete cover (mm) 30	40	50	60	70
CEM III/B	Life-365	C30/37	37.4	56.1	81.7	112.7	131.4
		C35/45	98.6	101.5	167.3	189.5	247.3
		C45/55	129.4	163.4	172.6	234.8	306.7
	Fib model	C30/37	38.7	59.64	78.1	99.65	141.6
		C35/45	101.3	153.1	163.7	178.3	265.7
		C45/55	128.7	157.6	172.4	241.3	311.5
CEM II/B-V	Life-365	C30/37	16.7	21.3	27.8	34.6	72.6
		C35/45	23.4	29.7	47.1	57.3	93.1
		C45/55	33.6	51.4	60.7	97.8	138.4
	Fib Model	C30/37	16.9	22.7	28.1	34.9	73.4
		C35/45	25.8	28.4	46.3	53.3	96.5
		C45/55	35.6	50.1	63.7	96.1	141.6
CEM I	Life-365	C30/37	11.7	15.6	18.6	39.3	55.9
		C35/45	16.3	19.8	29.7	37.4	78.4
		C45/55	19.7	25.8	36.5	48.7	96.3
	Fib Model	C30/37	13.4	15.3	16.8	19.4	57.1
		C35/45	17.1	19.4	27.6	38.7	77.6
		C45/55	18.9	15.3	33.4	53.6	89.7

Table 1 above presents the prediction of initiation time of corrosion of both models. The predicted initiation time of corrosion of the two models follows the same trend as there is no significant difference for the various cement types and concrete strength classes.

Table 2: Results for critical depth (mm) from the models

Table 2 shows the results of the various SCMs and the recommended durability values. It is presented according to the rank of performance of the SCMs.

		Minimum recommended concrete cover depth (mm)							
Cement type	Concrete strength class	Maximum surface chloride concentration 0.06	0.08	0.1	0.2	0.3	0.4	0.5	0.6
CEM II/B-V	C30/37	48	63	69	77	86	97	103	109
	C35/45	41	61	64	71	79	83	90	95
	C45/55	37	53	60	65	70	74	79	88
CEM III/B	C30/37	70	76	89	101	111	122	130	135
	C35/45	62	70	86	91	98	110	121	129
	C45/55	50	57	66	74	91	112	115	123
CEM I + 5% SF	C30/37	91	101	109	117	121	142	150	163
	C35/45	81	89	93	99	104	121	138	150
	C45/55	77	85	91	97	107	119	123	130
CEM 1	C30/37	151	176	183	194	207	231	252	265
	C35/45	143	155	172	189	194	211	232	243
	C45/55	109	121	132	149	156	170	181	189

The unit shows the results of the various SCMs and the recommended durability values. The most conservative results are selected and all other contradictory values (values above 150mm as are considered to be high) are ruled out and all other values less than 150mm were conventionally rounded up to the nearest 5mm. This is because of ease of construction and other structural constraint. As can be seen the use of CEM I cement type may not be suitable for application in most of the exposure conditions. While the use of CEM II/B-V was found to be efficient and suitable even under critical marine exposure conditions.

4.0 Discussion

4.1 Effect of cement type

It is evident from Figure 3.2 and 3.3 that SCM plays a key role in chloride ingress of concrete elements. Transport property mechanism of concrete is influenced by the cement type as widely known and this is demonstrated in the results. The ordinary PC shows poor performance in all the modelled scenarios which follows the same trend in most published literatures bearing in mind that SCMs improve durability of concrete in all ramifications. In this research, the performance of the various SCMs can be graded in the following order:
PC – 4; SF - 3; GGBFS – 2; FA - 1

The 35% FA performed significantly better than the other SCMs with considerable longer period to build up of chloride concentrations (almost close to the design life) and lesser diffusivity as presented in Figure 3.3 and 3.4 accordingly. In some recognised published literatures, the effect of FA on durability has been known (Bijan, 1996; Thomas, 2002). The use of FA can greatly reduce the rate of permeability chloride penetration especially in mature concrete because of pore structure refinement provided the concrete is adequately cured (Thomas, 2002). The application of GGBFS and SF equally revealed comparable characteristics in terms of concrete durability.

In general, the use of SCMs is a key factor enhancing durability of concrete in marine environment (Song, et al., 2008). Cement type influence the pore structure and binding capability of concrete, thus affecting durability.

4.2 Effect of concrete strength class

Figures 3.1 and 3.2 presents the influence of concrete grade on chloride ingress resistance. Concrete strength class is a key governing parameter in concrete durability. The results revealed that higher strength class shows a considerable effect to chloride resistance. Hydration of cement paste depends on the amount of water which is a major component of concrete strength class. Additional water is necessary to achieve effective compaction and to make the concrete workable. The process of chemical bonding enables the cement to be hardened, hence providing the concrete its strength.

Concrete strength class is therefore an essential design consideration to achieve required durability against corrosion. Decreasing the w/c ratio will achieve higher strength class, thus improving the pore structure and delay corrosion initiation period.

4.3 Cover to reinforcement

The study showed that cover depths affect the durability of reinforced concrete structures in marine environments in all ramifications which is the subject of this research. Higher cover depth helps to delay or prolong the time of chloride initiation and propagation in concrete structures in marine environments (Wang et al., 2010) as the period of initiation depends on the rate of movement of carbon dioxide and chlorine ions through the cover to the reinforcement surface. It is a less expensive and simple approach to reduce corrosion initiation and propagation in reinforced concrete.

5.0 Conclusions

The study dwell on the mechanism of chloride ingress, corrosion initiation and propagation, and problems associated with durability of reinforced concrete infrastructures in corrosive environments in conditions of climate change. The research found that SCMs, concrete strength class and concrete cover depth are good approaches that can be employed to improve the durability of reinforced concrete infrastructures in severe marine environments. The study also found that changing climate can affect the environmental conditions in a way that can accelerate corrosion initiation thus affecting the structural capacity and serviceability. Durability recommendations were made based on the result obtained which could help practicing engineers to make selection for RC structures made of various concrete types in order to reduce chloride-induced corrosion initiation within the service life of a structure in marine environments in conditions of climate change.

As the issue of sustainability becomes considerably essential, one of the main mitigation measures is the reduction of global anthropogenic CO_2 emissions, about 5% of which come from cement production that is an important part of the concrete industry. CO_2 emissions associated with concrete production can be reduced by partially replacing the amount of Portland cement with other supplementary cementitious materials used for this production.

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